TMR4585

Positioning and navigation

2019

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Kahoot

Learning objectives

- Kinematics and reference frames
- Concepts for navigation and positioning
  - Acoustic positioning
  - Dead reckoning
  - Inertial navigation
- Navigation instruments
- Error budgets
- Calibrations

Curriculum Positioning and navigation

- Hegrenes 2010*
- Paull 2014*
- Anonsen 2013*
- Kebkal 2013*
- Survey handbook
- Lecture notes TMR4120*

Terms and defintions

- Positioning
  - Baseline
- Navigation
  - Dead reckoning
  - Free interial navigation
- Accuracy
  - Error budget
  - Calibrations

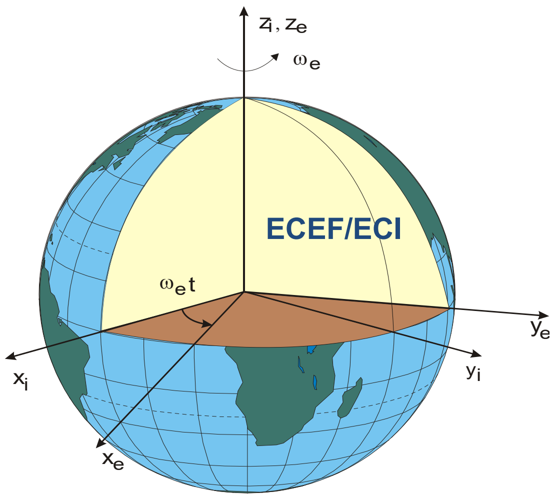
Kinematics and Kinetics

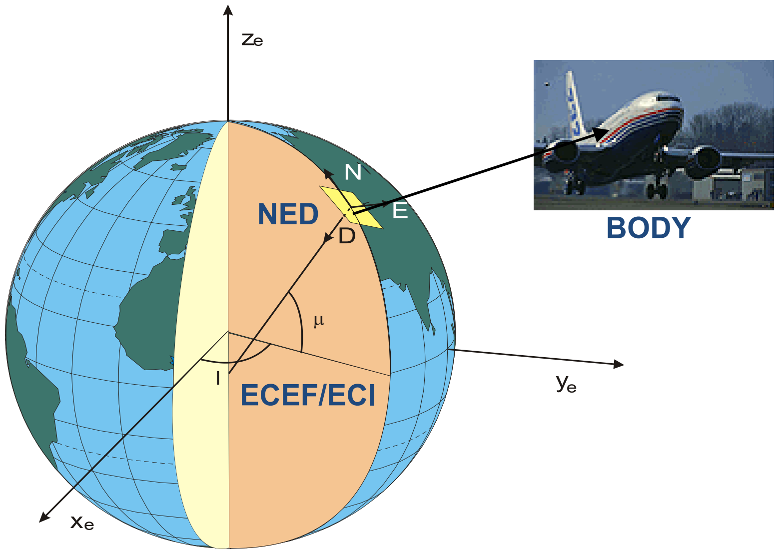
- The study of dynamics is divided into two main areas:
  - Kinematics
  - Kinetics

- Kinematics describes geometrical aspects of motion without considering mass and forces: reference frames, variables and transformations. Normally no uncertainty is associated with the kinematics.

- Kinetics describes the effects of forces and mass on the motion. The kinetics is involved including hydrodynamics.

Reference Frames





- ECI (i-frame): Earth-Centered Inertial frame; non-accelerating frame in which Newton's laws of motion apply.
- ECEF (e-frame): Earth-Centered Earth-Fixed frame; origin is fixed in the center of the Earth but the axes rotate relative to the inertial frame ECI.
- **NED (n-frame): North-East-Down frame; defined relative to the Earth's reference ellipsoid (WGS 84).**
- **BODY (b-frame): Body frame; moving coordinate frame fixed to the vessel.**

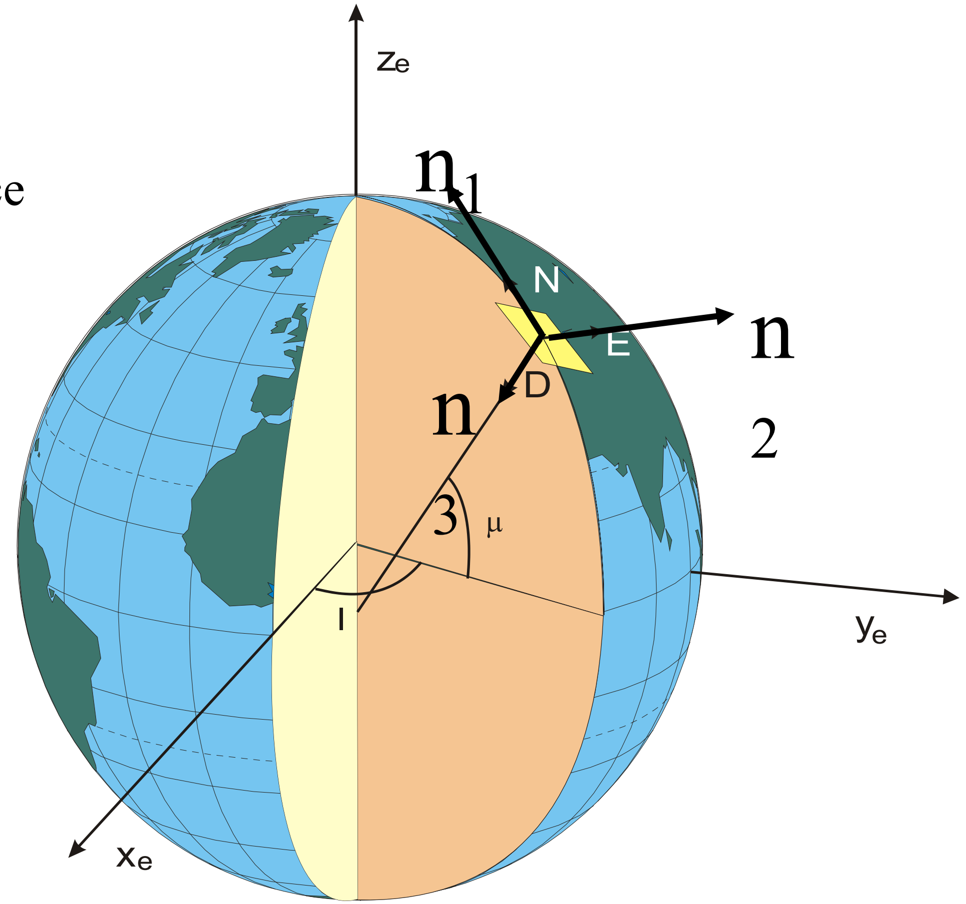
  x_b- longitudinal axis (directed from aft to fore)

  y_b- transversal axis (directed to starboard)

  z_b-normal axis (directed from top to bottom)

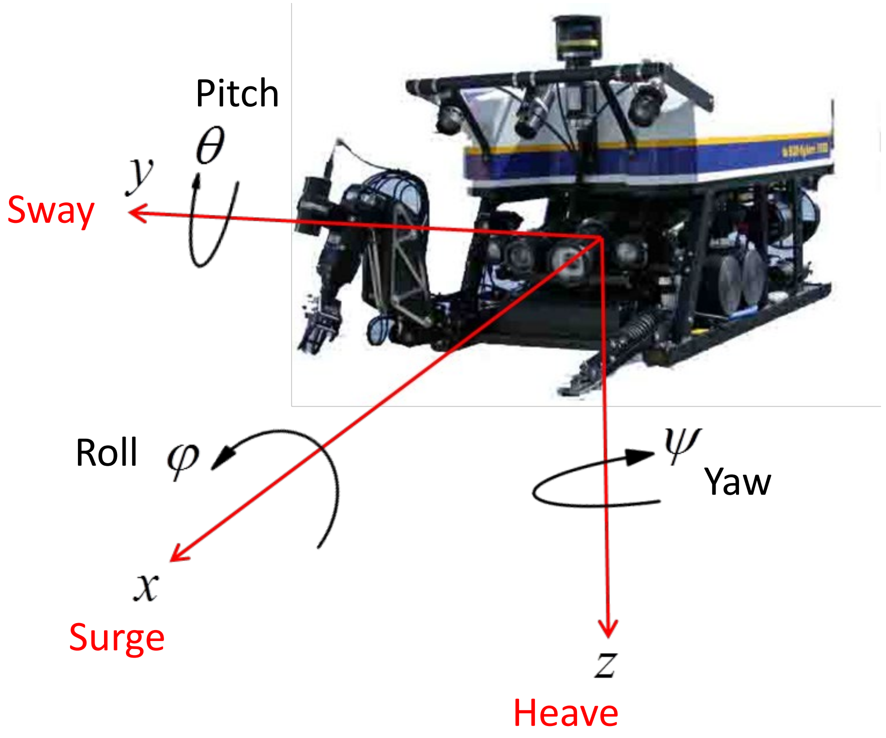
North-East-Down Frame (*n*-frame)

- The frame (o_n, n_1, n_2, n_3) is a local geographical frame fixed to the Earth, defined relative to the Earth's reference ellipsoid (WGS 84).
- The positive unit vector n_1 points towards the North, n_2 points towards the East, and n_3 points towards the centre of the Earth.
- The origin, o_n, is located on mean water free-surface at an appropriate location.
- This frame is considered inertial.



Body-Fixed Frame (*b*-frame)

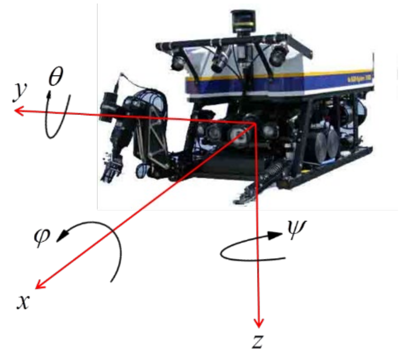
- The frame (o_b, b_1, b_2, b_3) is fixed to the hull.
- The positive unit vector b_1 points towards the bow, b_2 points towards starboard and b_3 points downwards.
- For marine vehicles, the axes of this frame are chosen to coincide with the principal axes of inertia; this convention determines the position of the origin of the frame, o_b.
- Right-hand system defines the sign of the rotations



Kinematics Relations

Linear and angular velocity of vessel in body-fixed frame relative to earth-fixed frame for 6 DOF - surge, sway, heave, roll, pitch and yaw:

$$\dot{\eta} = \begin{bmatrix} \dot{\eta}_1 \\ \dot{\eta}_2 \end{bmatrix} = \begin{bmatrix} J_1(\eta_2) & 0_{3\times 3} \\ 0_{3\times 3} & J_2(\eta_2) \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix} = J(\eta)\nu$$



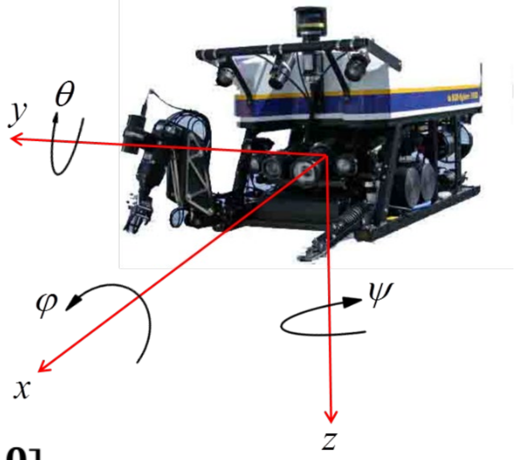
Earth-fixed position and orientation vectors are:

$$\eta_1 = [x \quad y \quad z]^T, \eta_2 = [\phi \quad \theta \quad \psi]^T$$

Linear and angular vessel velocity vectors in body-fixed frame are defined:

$$\nu_1 = [u \quad v \quad w]^T, \nu_2 = [p \quad q \quad r]^T$$

Kinematics Relations Using Euler Angles



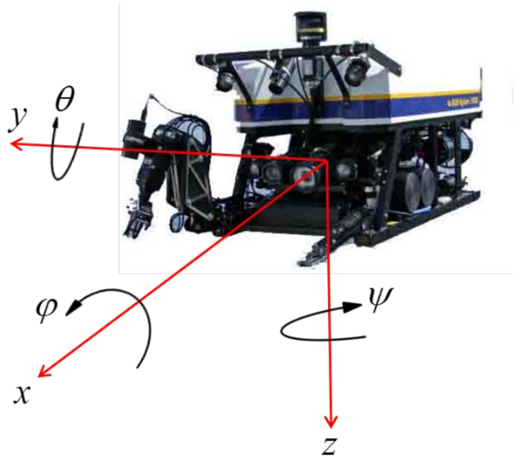
$$R_{x,\phi} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c\phi & -s\phi \\ 0 & s\phi & c\phi \end{bmatrix}, R_{y,\theta} = \begin{bmatrix} c\theta & 0 & s\theta \\ 0 & 1 & 0 \\ -s\theta & 0 & c\theta \end{bmatrix}, R_{z,\psi} = \begin{bmatrix} c\psi & -s\psi & 0 \\ s\psi & c\psi & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

$$R(\phi, \theta, \psi) = R_{x,\phi}(\phi) * R_{y,\theta}(\theta) * R_{z,\psi}(\psi)$$

$$\dot{\eta} = R(\phi, \theta, \psi) * \nu$$

Kinematics Relations Using Euler Angles

$$\dot{\eta} = \begin{bmatrix} \dot{\eta}_1 \\ \dot{\eta}_2 \end{bmatrix} = \begin{bmatrix} J_1(\eta_2) & 0_{3\times3} \\ 0_{3\times3} & J_2(\eta_2) \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \end{bmatrix} = J(\eta)\nu$$



Where $J_1(\ )$ and $J_2(\ )$ are Euler rotation matrices.

$$\mathbf{J}_1(\eta_2) = \begin{bmatrix} c\psi c\theta & -s\psi c\phi + c\psi s\theta s\phi & s\psi s\phi + c\psi c\phi s\theta \\ s\psi c\theta & c\psi c\phi + s\phi s\theta s\psi & -c\psi s\phi + s\theta s\psi c\phi \\ -s\theta & c\theta s\phi & c\theta c\phi \end{bmatrix}$$

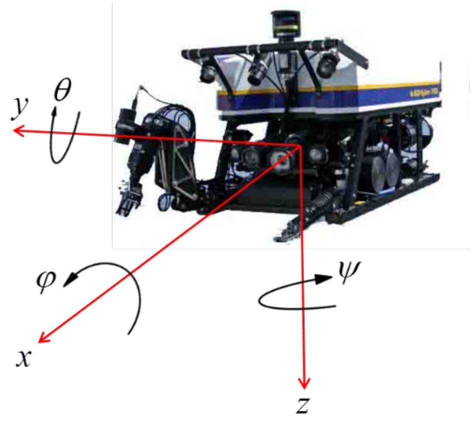
$$\nu_2 = \begin{bmatrix} \dot{\phi} \\ 0 \\ 0 \end{bmatrix} + C_{x,\phi} \begin{bmatrix} 0 \\ \dot{\theta} \\ 0 \end{bmatrix} + C_{x,\phi} C_{y,\theta} \begin{bmatrix} 0 \\ 0 \\ \dot{\psi} \end{bmatrix} = J_2^{-1}(\eta_2)\dot{\eta}_2$$

$$\mathbf{J}_2(\eta_2) = \begin{bmatrix} 1 & s\phi t\theta & c\phi t\theta \\ 0 & c\phi & -s\phi \\ 0 & s\phi / c\theta & c\phi / c\theta \end{bmatrix} \quad c\theta \neq 0$$

$$\mathbf{J}_1^{-1}(\eta_2) = \mathbf{J}_1^T(\eta_2) \qquad \mathbf{J}_2^{-1}(\eta_2) \neq \mathbf{J}_2^T(\eta_2)$$

Manoeuvring Coordinates - Summary

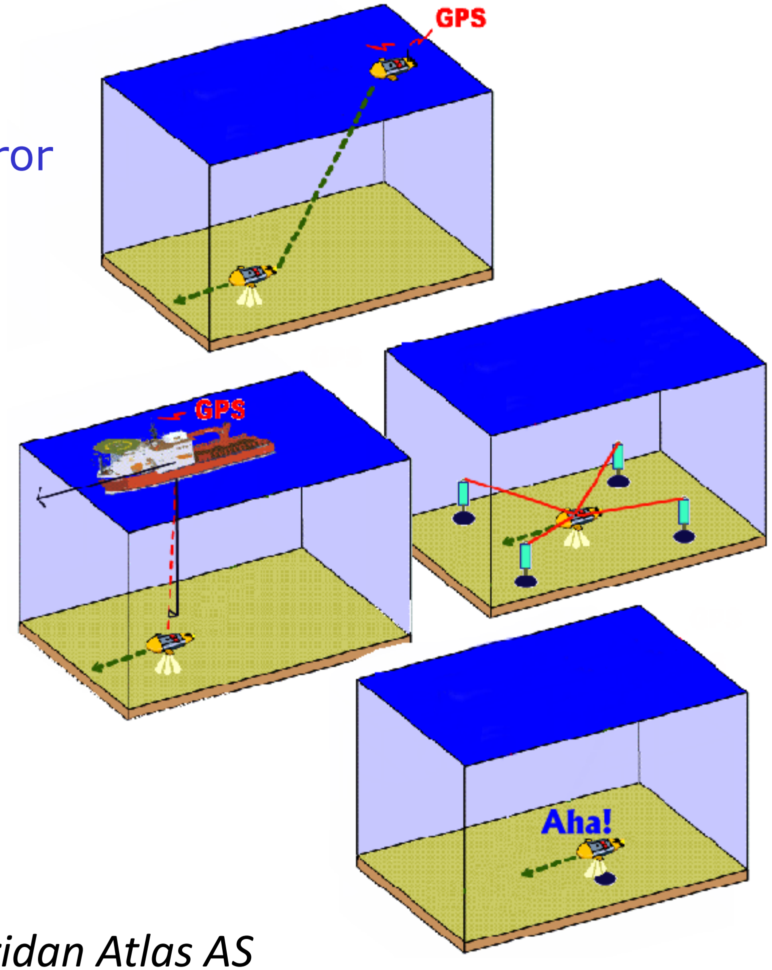
Coordinate	Name	Definition frame
n	North position	n-frame
e	East position	n-frame
d	Down position	n-frame
ϕ	Roll angle	Euler angle $(n \rightarrow b)$
θ	Pitch angle	Euler angle $(n \rightarrow b)$
ψ	Heading or yaw angle	Euler angle $(n \rightarrow b)$
u	Surge velocity	b-frame
v	Sway velocity	b-frame
w	Heave velocity	b-frame
p	Roll rate	b-frame
q	Pitch rate	b-frame
r	Yaw rate	b-frame



This notation is adopted from SNAME (1950): Nomenclature for Treating the Motion of a Submerged Body Through a Fluid. *The Society of Naval Architects and Marine Engineers, Technical and Research Bulletin No. 1-5, April 1950, pp. 1-15.*

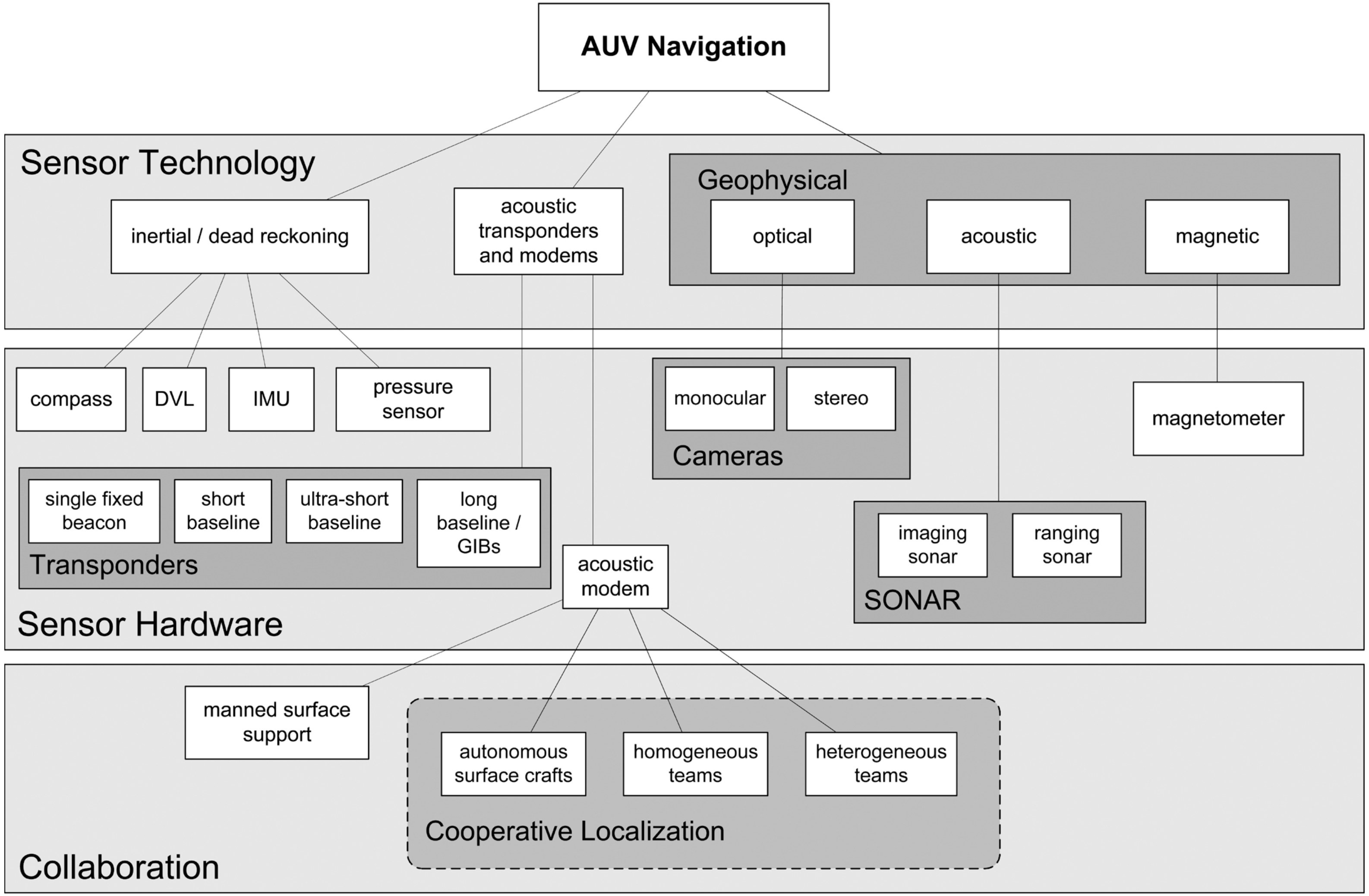
Navigation

- **Dead reckoning**
  +Autonomy (simple operations)
  - Inherently unbounded position error
  - Dive error
  - QC of navigation data
- **Acoustic positioning**
  +Accuracy (?)
  +Proven/known technology
  - Costly and time consuming operations (+UGPS)
  - Cumbersome and error prone
- **Geophysical navigation**
  +Autonomy (?)
  - Dive error
  - Complexity



Maridan Atlas AS

Classification of underwater navigation



Paull 2014

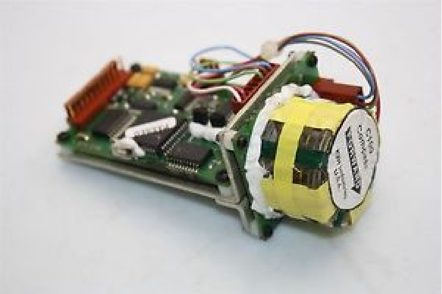
Finding north (7 ways)

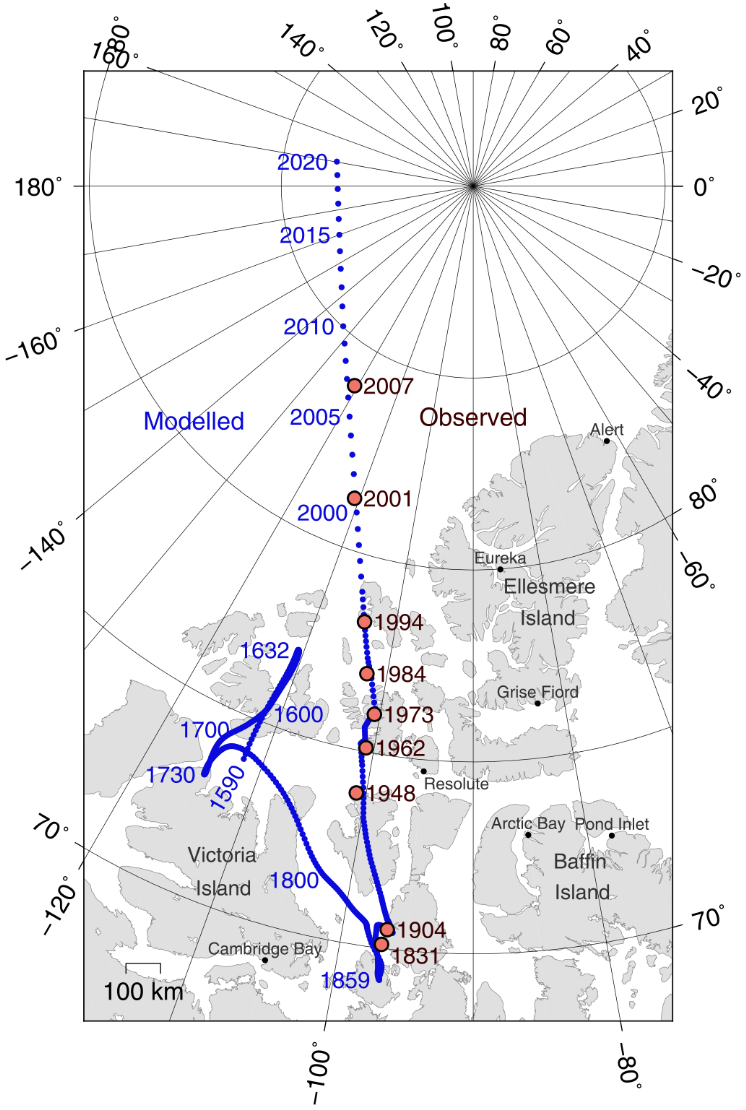
1. Magnetic compass
2. Gyro compassing
3. Observing multiple objects
   - Solar tracker
   - Downward AUV camera
4. Measure bearing to an object with a known position
5. Multi-antenna GNSS
6. Vehicle velocity
7. Vehicle acceleration

The seven ways to find heading, K. Gade 2016 Journal of navigation

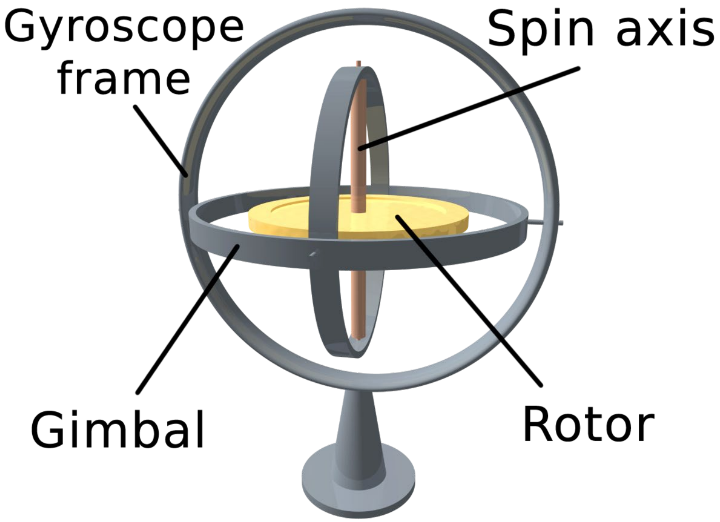
Heading sensors

- Magnetic compass
  - Typical accuracy: 5°
  - Magnetic North
  - Inexpensive
  - Slow transient behavior
  - Affected by magnetic disturbances
- Gyro compassing
  - Typical accuracy: 0.1° / cos(lat)
    - 0.25° in Trondheim
    - 0.50° in Svalbard
  - True North
  - Expensive
  - High power consumption

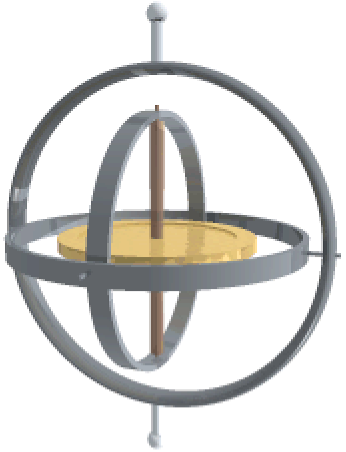




Gyroscopes

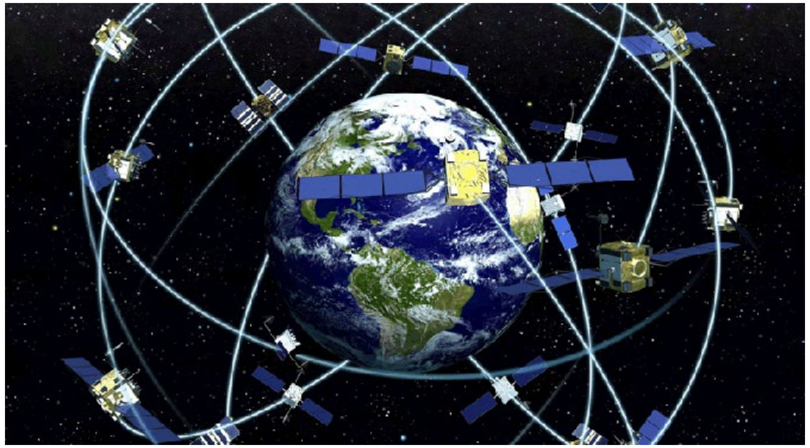


- Maintain angular momentum.
  - Spinning wheel.
  - Gimball positions.
- Sagnac effects.
  - Inertial characteristics of light / interference pattern
  - Beam in a loop.
  - Ring laser / fiber optic.
- Coriolis effect.
  - Tuning fork.
  - MEMS gyros.



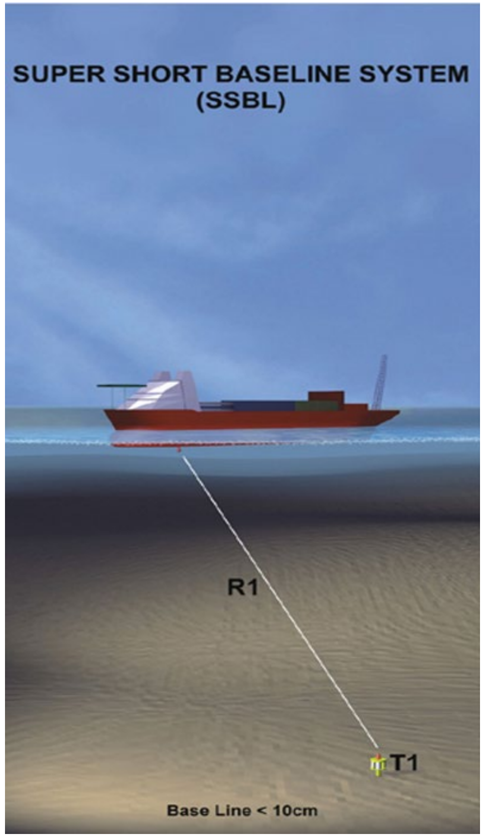
Global navigation satellite system (GNSS)

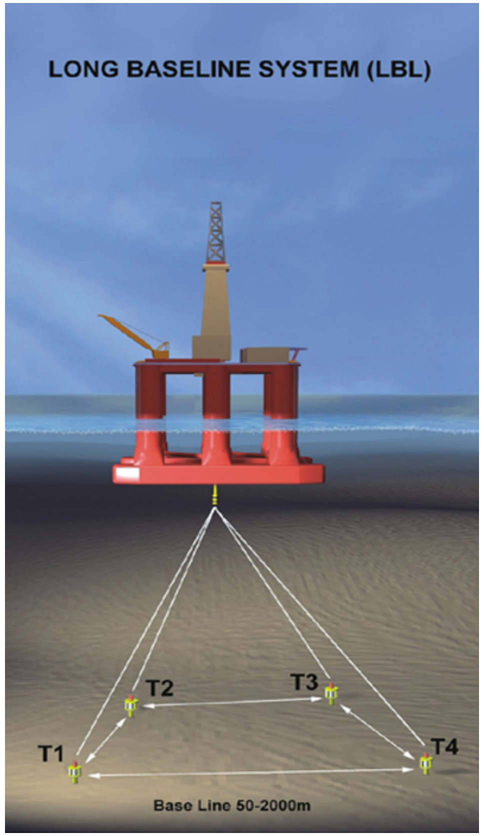
- GPS, GLONASS, Galileo, BeiDou, QZSS, NAVIC
  - 1 - 15 meter horizontal deviation (public)
- GLONASS, Galileo, BeiDou
  - 0.01 – 0.1 meter precision (encrypted)
- dGPS
  - 0.1 - 5 meter precision
- Real-time kinematic (RTK)
  - Signal carrier wave
  - Position ambiguity
  - Fixed base station
  - 0.01 meter horizontal deviation possible

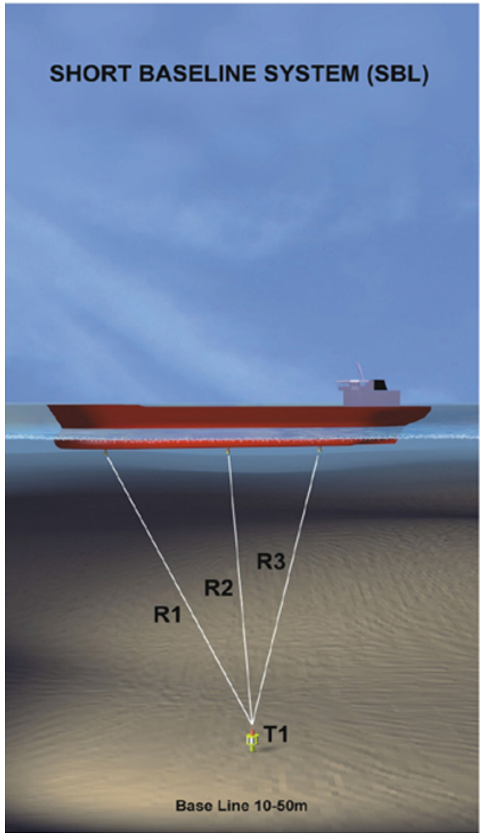


For underwater navigation, GNSS is only useful in the surface.

Acoustic Navigation Principles

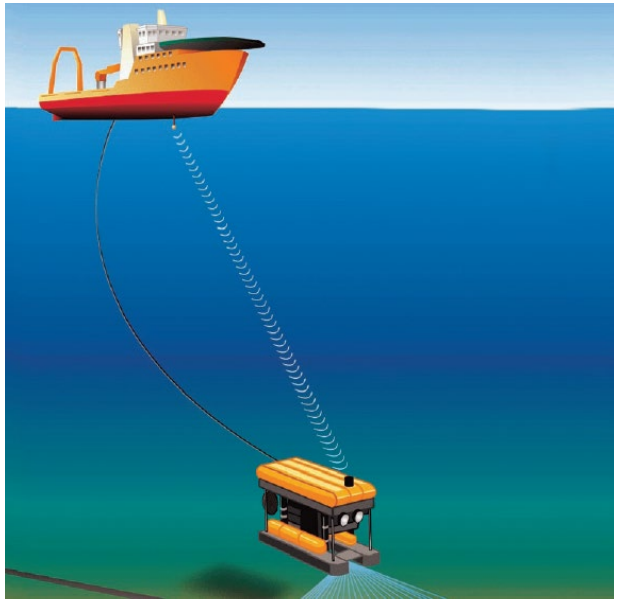






Courtesy to Kongsberg Maritime

Acoustic Navigation Principles



Courtesy to Kongsberg Maritime

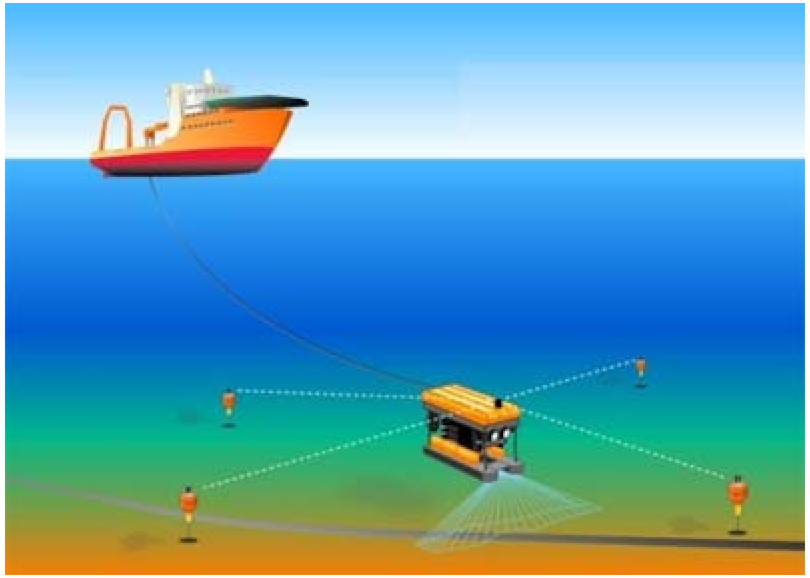
- A hydroacoustic positioning system consists of both a transmitter (transducer) and a receiver (transponder).
- A signal (pulse) is sent from the transducer, and is aimed towards the seabed transponder or ROV transponder. This pulse activates the transponder, which responds immediately to the vessel transducer.
- The transducer, with corresponding electronics, calculates an accurate position of the e.g. ROV transponder relative to the vessel

NAVIGATION – LBL?

Conventional LBL "Longer to install, calibrate and recover array than to perform Survey"

Long baseline navigation

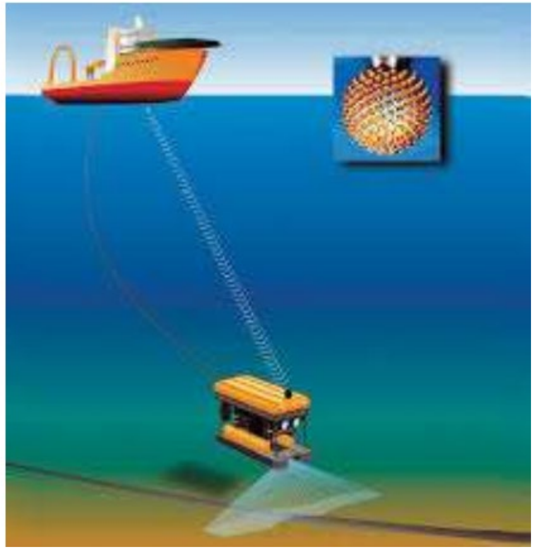
- Range to multiple transponders
- Increased accuracy
- Installation

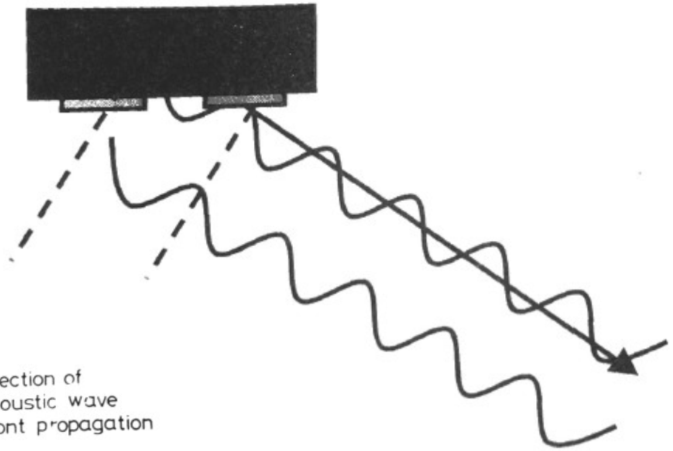


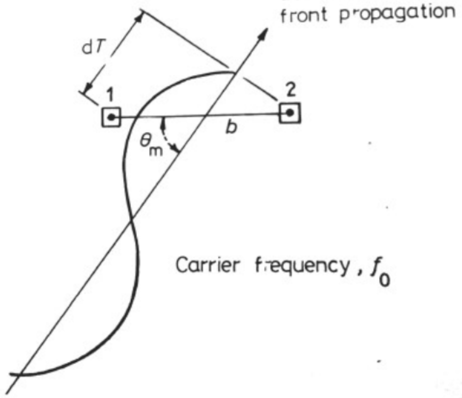
NAVIGATION – SLBL?
Why 'Synthetic'?

USBL navigaton

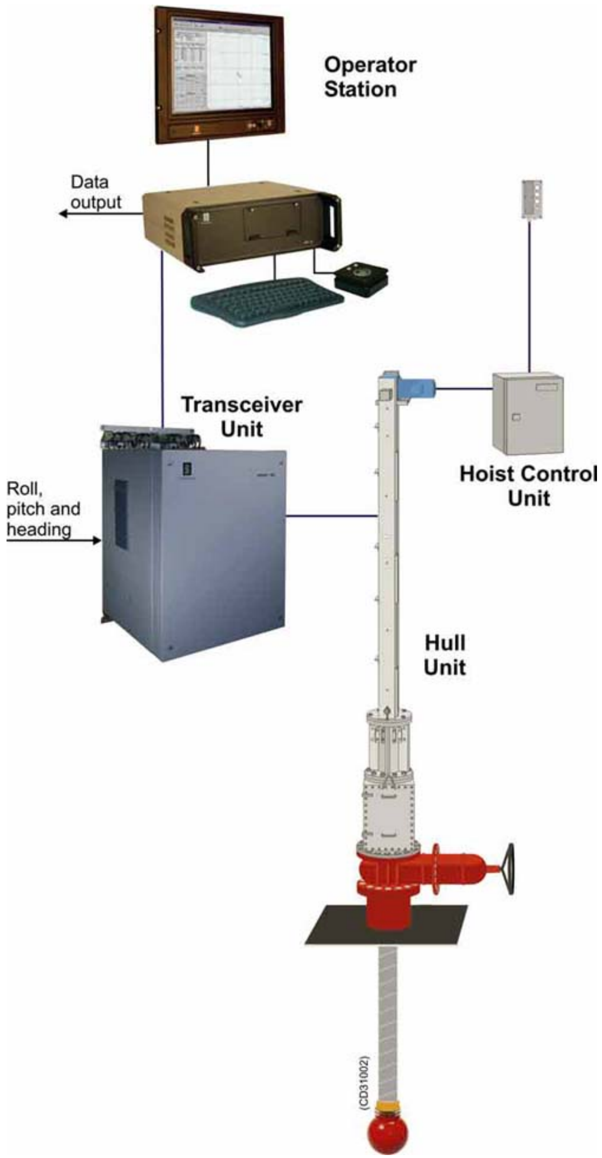
- Range
- Depression angle
- Asimuth angle





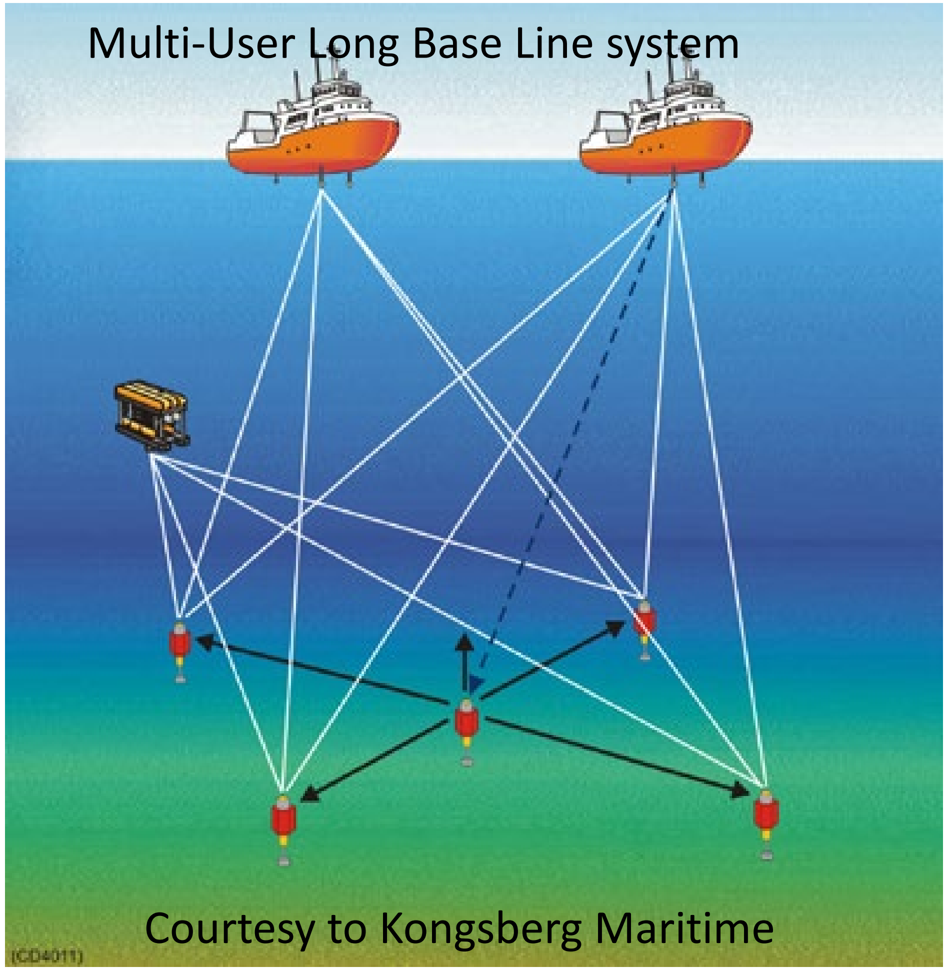


Acoustic Positioning Reference System USBL/SSBL– HiPAP (Mounted on ship)



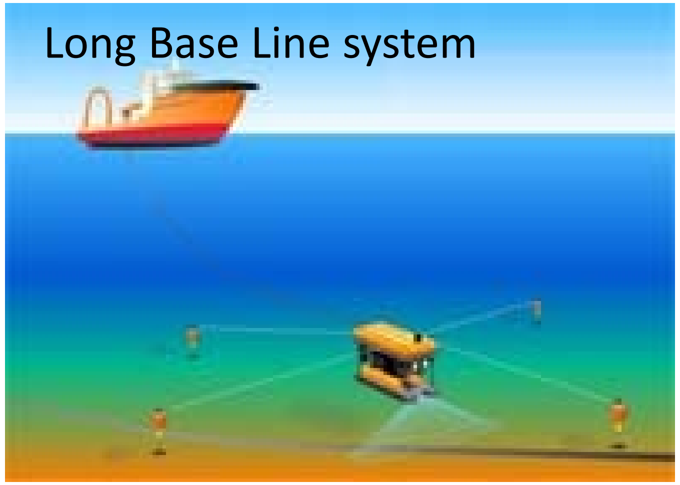
- USBL
  - Transponder
- States:
  - [x,y,z]
- Issues:
  - Low update frequency (1-2 s)
  - Lag
  - Accuracy
  - Water column
  - Accuracy noise dependent

Acoustic Navigation Principles



Most used underwater navigation for AUV and ROV:

- Super short base line system (SSBL) / ultra short base line system (USBL)
- Long base line system (LBL)



Positioning

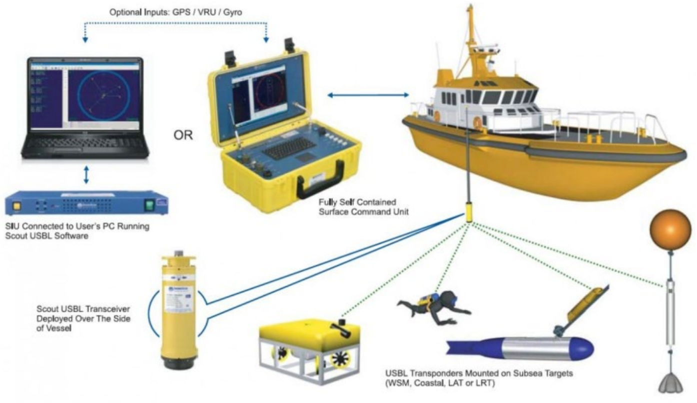


Image: Seløy AS

Set up acoustical navigation

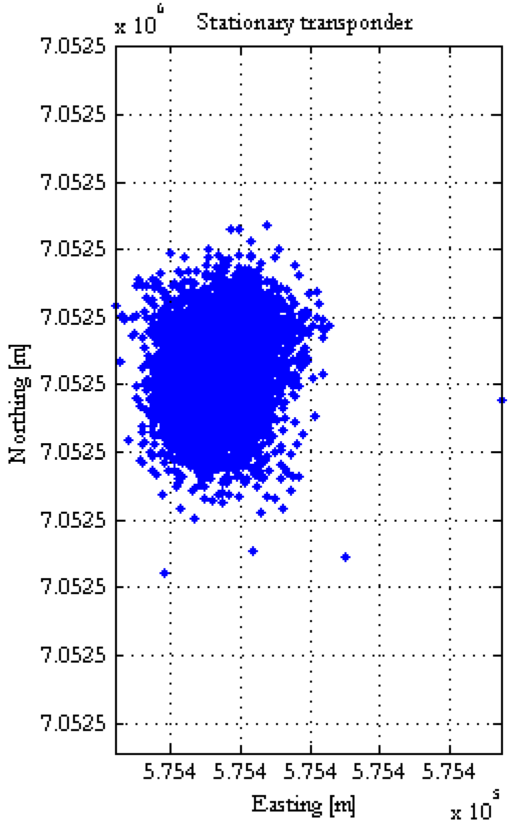
- USBL
- LBL

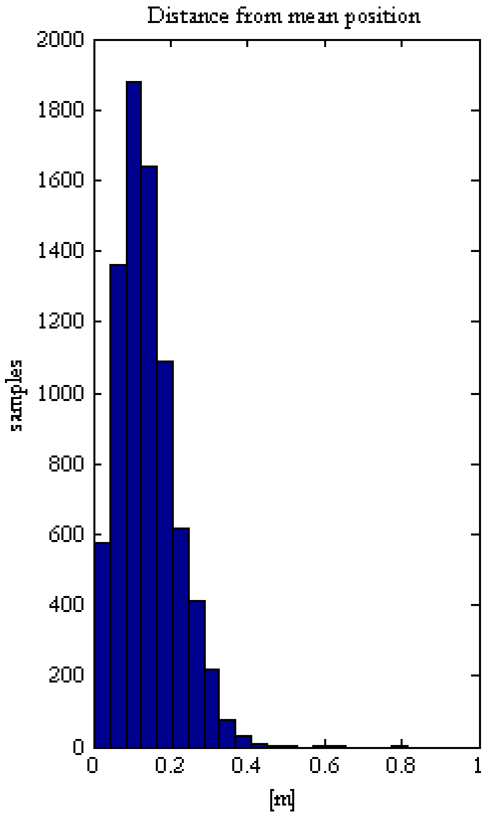
Instruments:

- Heading sensors
- GPS
- Pressure sensors
- DVL
- IMU

- Quality assessment
  - Calibration
  - Error budgets

Example data set





Typical USBL system performances

Manufacturer	Product name	Frequency	Frequency Band	Accuracy Range	Accuracy angular
Kongsberg	HiPAP 500	21 – 31 kHz	MF	0.1 m	**0.12°**
Maritime	HiPAP 100	10 – 15.5 kHz	LF	0.1 m	**0.14°**
Sonardyne	Scout	35 – 55 kHz	HF	**0.5 % of range**	
	Fusion	18 – 36 kHz	MF	**0.2 % of range**	
		35 – 55 kHz	HF		
Link-Quest	Tracklink 1500	31 – 43.2 kHz	HF	0.2 m	**3.0° - 0.25°**
	Tracklink 5000	14.2 – 19.8 kHz	MF	0.3 m	**3.0 ° - 0.15°**
	Tracklink 10000	8.4 – 11.7 kHz	LF	0.4 m	**3.0° - 0.25°**
Applied acoustics	Easy Trak	17 – 32 kHz	MF	0.1 m	**1.4°**
IXSEA	Posidonia	8 – 18 kHz	LF	**0.3 % of range**	
	GAPS	20 – 30 kHz	MF	**0.2 % of range**	
ORE	**Trackpoint 3**	**8 – 30 kHz**	**MF**	**0.5 % of range**	

Pressure sensor

- Depth
- States:
  - [z]
- Calculated
  - Polynom for densitity
  - Fixed density
- Issues:
  - Wave zone
  - Density profile
  - Tides
  - Gravity
  - Atmospheric pressure

$$d = \frac{p_t - p_a}{\rho \cdot g}$$

$$\rho(S,T,P) = \frac{\rho(S,T,0)}{\left[\frac{1-p}{K(S,T,P)}\right]}$$

Doppler velocity log (DVL)

- Doppler shift
- Doppler velocity log (DVL)
  - Velocity relative to water or seafloor
- States:
  - [u, v, w]
  - Altitude
  - Bathymetry (sparse)
- Issues:
  - altitude>100m
  - Pitch angle.
- Bottom track vs water track

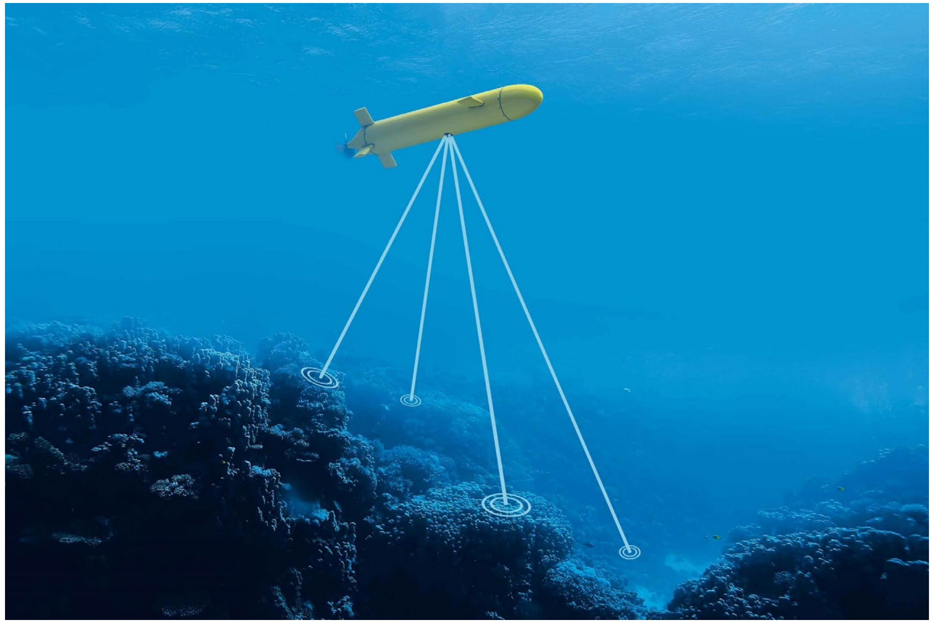


Image courtesy of Nortek

Doppler effect

- $f_d = 2f_0 \frac{v_r}{c}$
- v_r is positive when moving closer, negative when moving away

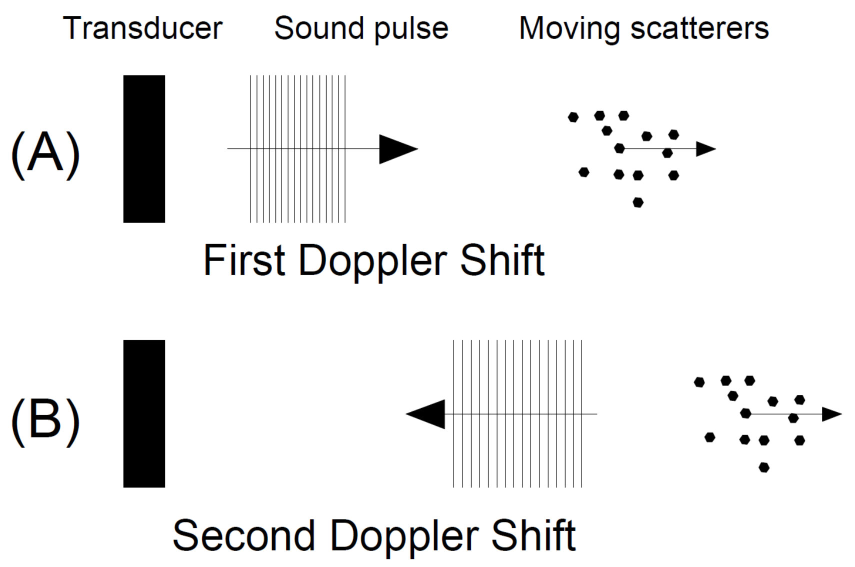


Figure from Teledyne RD Instruments

Inertial measurement unit (IMU)

- Sensors:
  - 3 accelerometers
  - 3 gyroscopes
  - 3 magnetometers
- States:
  - Attitude [roll, pitch, yaw]
  - Rotational velocity [p,q,r]
  - Accelerations.
- Issues:
  - Magnetic disturbances
  - Gyro drift
  - Bias
  - Lever arm

Resulting accuracy USBL system

- Surface ship position (GPS) accuracy
- USBL measurement accucy
- System installation accuracy
- Surface ship attitude accuracy
- Sound velocity profile (SVP) accuracy

Error propagation

$$x = f(a, b, c)$$

$$dx_i = f(da_i, db_i, dc_i)$$

$$dx = \left(\frac{\delta x}{\delta a}\right)_{b,c} da, \; \left(\frac{\delta x}{\delta b}\right)_{a,c} db, \; \left(\frac{\delta x}{\delta c}\right)_{a,b} dc$$

$$\sigma_x^2 = \left(\frac{\delta x}{\delta a}\right)^2 \sigma_a^2 + \left(\frac{\delta x}{\delta b}\right)^2 \sigma_b^2 + \left(\frac{\delta x}{\delta c}\right)^2 \sigma_c^2$$

$$x = a + b - c \qquad \sigma_x = \sqrt{{\sigma_a}^2 + {\sigma_b}^2 + {\sigma_c}^2}$$

Assuming cross terms cancel out

NTNU

Error propagation for a USBL set up

- USBL positioning

$$P_{USBL} = P_S + \begin{bmatrix} c_\omega & -s_\omega & 0 \\ s_\omega & c_\omega & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} c_\nu & 0 & s_\nu \\ 0 & 1 & 0 \\ -s_\nu & 0 & c_\nu \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ r \end{bmatrix} = P_S + \begin{bmatrix} c_\omega s_\nu \\ s_\omega s_\nu \\ c_\nu \end{bmatrix} r$$

$$P_{USBL} = P_S + R_{z,\omega} R_{y,\nu} \left[0, 0, r\right]^T$$

$$\sigma^2_{USBL,X} \approx \sigma^2_{S,X} + \left(\frac{\delta X}{\delta \omega}\right)^2 \sigma^2_\omega + \left(\frac{\delta X}{d\nu}\right)^2 \sigma^2_\nu + \left(\frac{\delta X}{\delta r}\right)^2 \sigma^2_r$$

$$\sigma^2_{USBL,X} \approx \sigma^2_{S,X} + \left(\frac{\delta c_\omega s_\nu r}{\delta \omega}\right)^2 \sigma^2_\omega + \left(\frac{\delta c_\omega s_\nu r}{\delta \nu}\right)^2 \sigma^2_\nu + \left(\frac{\delta c_\omega s_\nu r}{\delta r}\right)^2 \sigma^2_r$$

$$\sigma^2_{USBL,X} \approx \sigma^2_{S,X} + (-s_\omega s_\nu r)^2 \sigma^2_\omega + (c_\omega c_\nu r)^2 \sigma^2_\nu + (c_\omega s_\nu)^2 \sigma^2_r$$

Examples from Hegrenæs 2010

TABLE I

AUV HORIZONTAL POSITION UNCERTAINTY (1σ) DUE TO HIPAP 500 MEASUREMENT UNCERTAINTY AT 20 DB AND 0.2 M (1σ) SURFACE SHIP GPS UNCERTAINTY. THE RELATIVE HORIZONTAL POSITION BETWEEN THE AUV AND THE USBL TRANSDUCER IS X = 50 M, Y = 50 M.

AUV depth [m]	50	100	500	1000	3000
AUV position uncertainty [m]	0.32	0.35	1.08	2.11	6.29

TABLE II

AUV HORIZONTAL POSITION UNCERTAINTY (1σ) DUE TO SHIP ATTITUDE UNCERTAINTY OF $0.01°$ (1σ) IN ROLL AND PITCH, AND $0.1°$ (1σ) IN HEADING. THE SHIP ATTITUDE IS $\phi = 0°, \theta = 0°, \psi = 0°$. THE RELATIVE HORIZONTAL POSITION BETWEEN THE AUV AND THE USBL TRANSDUCER IS X = 50 M, Y = 50 M.

AUV depth [m]	50	100	500	1000	3000
AUV position uncertainty [m]	0.12	0.13	0.17	0.28	0.75

TABLE III

AUV HORIZONTAL POSITION UNCERTAINTY (1σ) DUE TO USBL TRANSDUCER ALIGNMENT UNCERTAINTY OF $0.05°$ (1σ) IN ROLL AND PITCH, AND $0.1°$ (1σ) IN HEADING. THE TRANSDUCER ALIGNMENT IS $\phi' = 0°$, $\theta' = 0°$, $\psi' = 0°$. THE RELATIVE HORIZONTAL POSITION BETWEEN THE AUV AND THE USBL TRANSDUCER IS X = 50 M, Y = 50 M.

AUV depth [m]	50	100	500	1000	3000
AUV position uncertainty [m]	0.14	0.18	0.63	1.24	3.71

Calibrations

Item	Minimum calibration frequency	Calibration procedure	Allowable tolerance
USBL transducer	Initial installation	Offsets	**< 0.5°**
Gyro	Initial installation and at start of each project	Operator's gyro/heading sensor calibration procedures	**< 0.5°**
Roll/pitch	Start of each project	Per manufacturer's procedures	**< 0.1°**
GPS	Initial installation and checked at start of each project	Offsets	**~ 2.5 cm**
Sound velocity	**As many as required to sustain necessary precision**		**0.2 – 0.3 m + 0.5 % x water m/sec**

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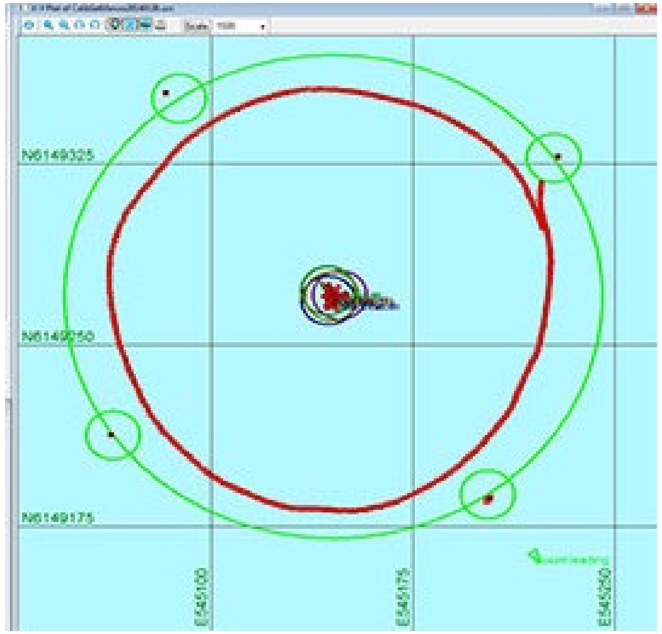
Innovation and Creativity

USBL Calibrations

- Box in test
- Spin test
- Error components
  - Scaling error
  - Velocity error
  - Horizontal alignment of system reference frames
  - Gyro error
  - Transducer alignment
  - Vertical alignment of system reference frames
  - Pitch error
  - Roll error



Calibrations

- DVL
  - Long line both directions (1-1.5 hours)
- Gyro
  - Surveyor
- Pressure
  - Vendor procedure
- GPS
  - HDOP
  - VDOP

Calibrations

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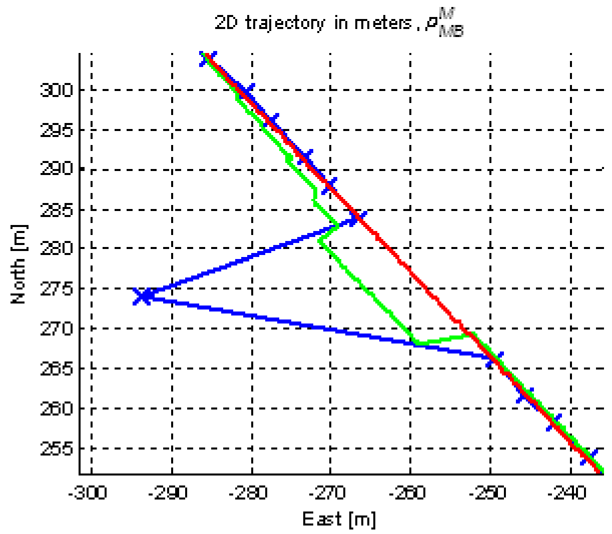
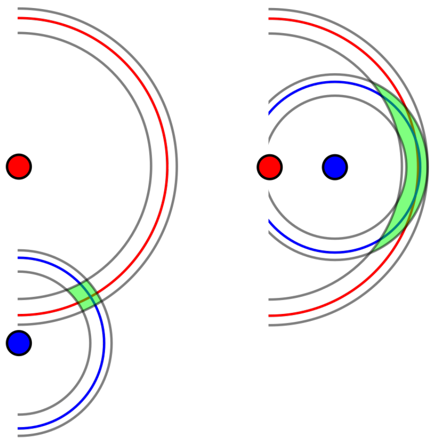
Real time measurement errors

- Signal freeze
- Signal drop-out
- Low signal-to-noise ratio (SNR)
- High bias
- Wild points (jumps)
- Dilution of precision (DOP)

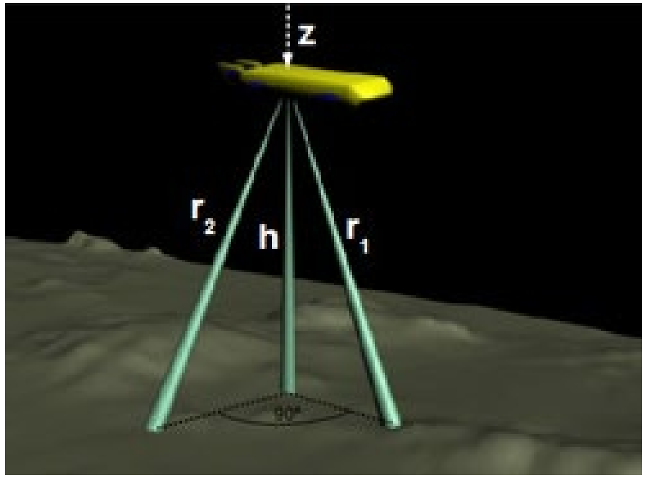


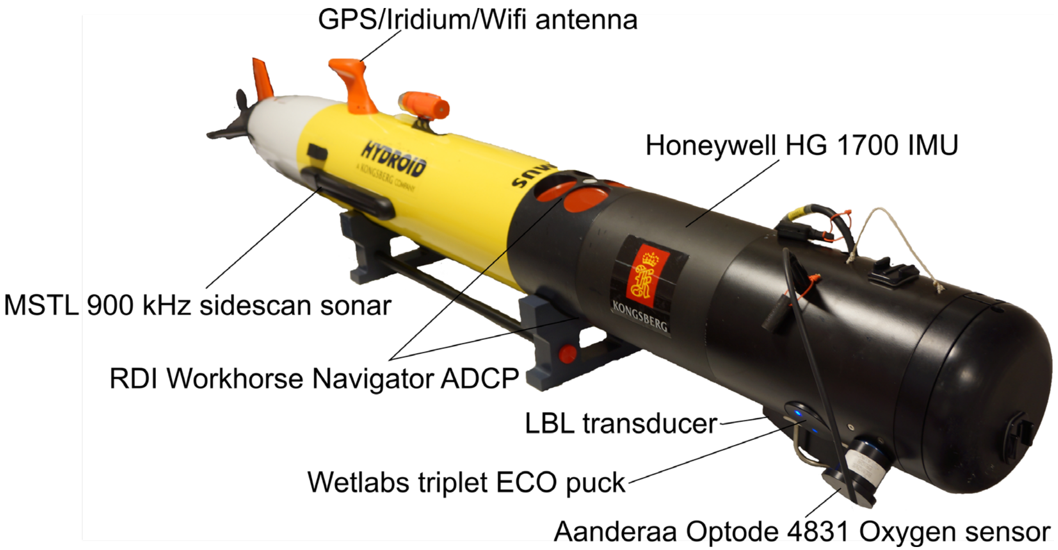
Courtesy: www.navlab.net



Navigation - AUV

- Concepts
  - USBL
  - LBL
  - Dead reckoning / Inertial nav.
  - Terrain navigation
  - SLAM
- Instruments
  - IMU
- Quality assessment





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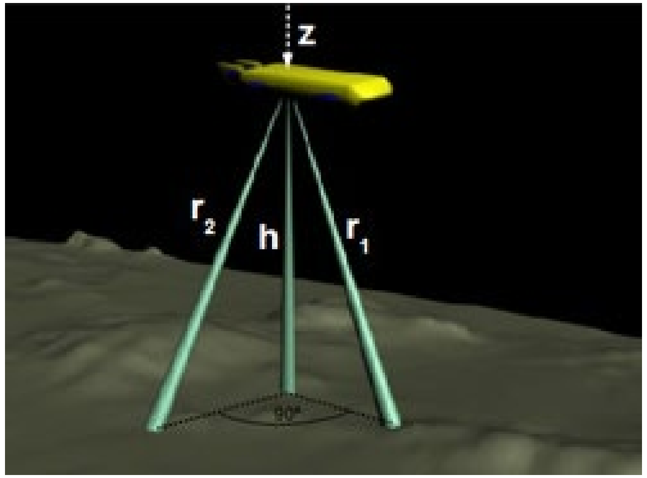
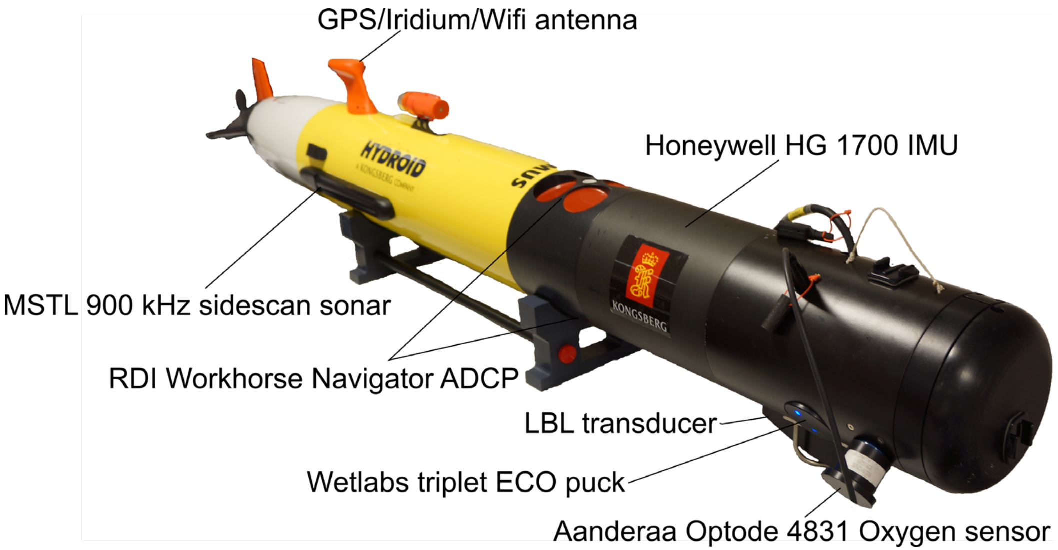
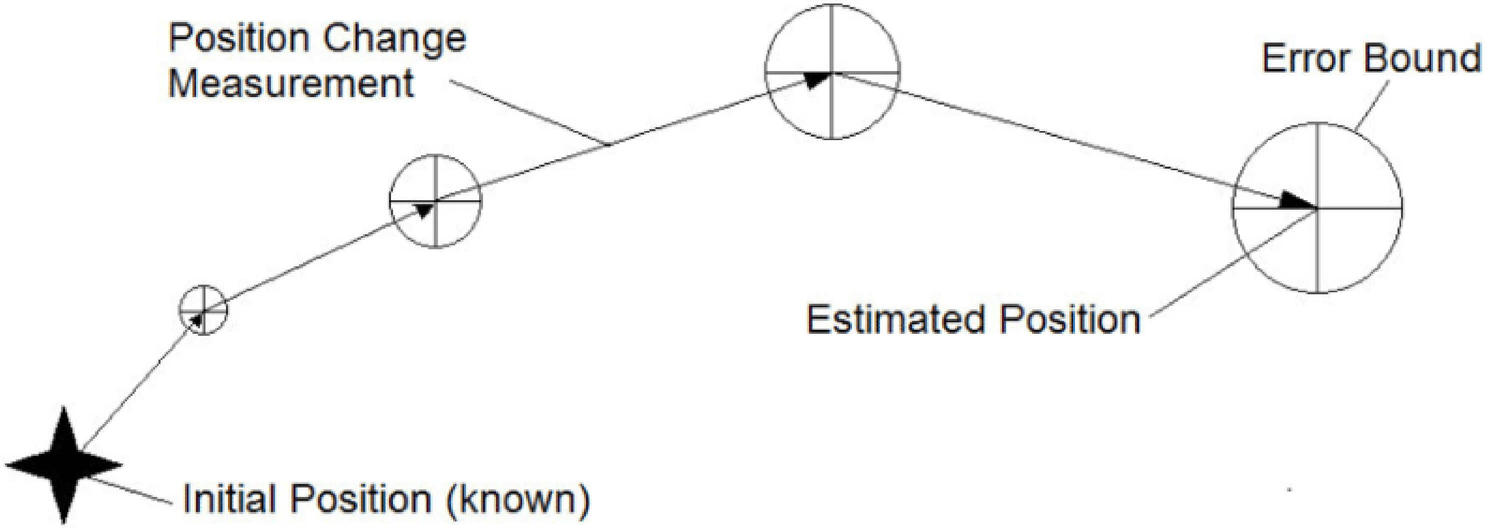




Dead reckoning concept

- Process of estimating the position from a previously known location.
- That is, the current position can be found from (Euler's method):

$$x_t = x_{t-1} + h\dot{x}_{t-1} + O(h^2) \approx x_{t-1} + h\dot{x}_{t-1}$$



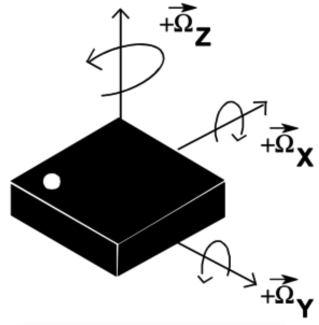
Dead reckoning measurements

Measurements of:

- Time.
- Orientation.
- Acceleration.
- Velocity.

Using:

- Accelerometers.
- Gyroscopes.



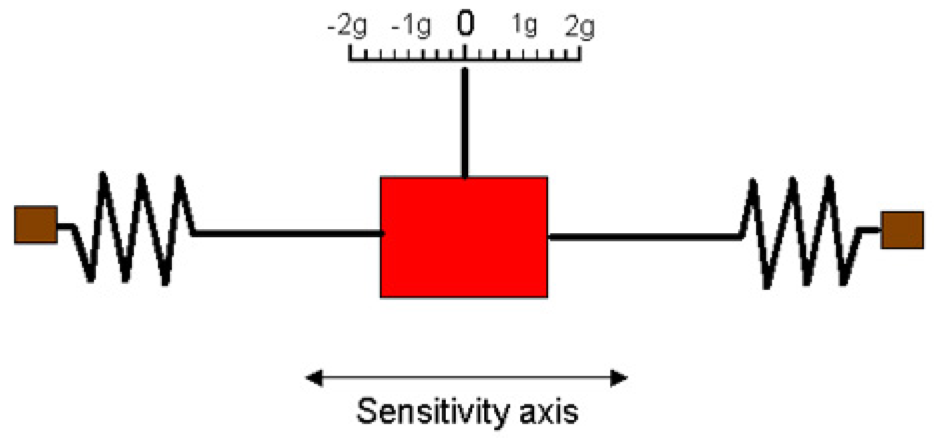
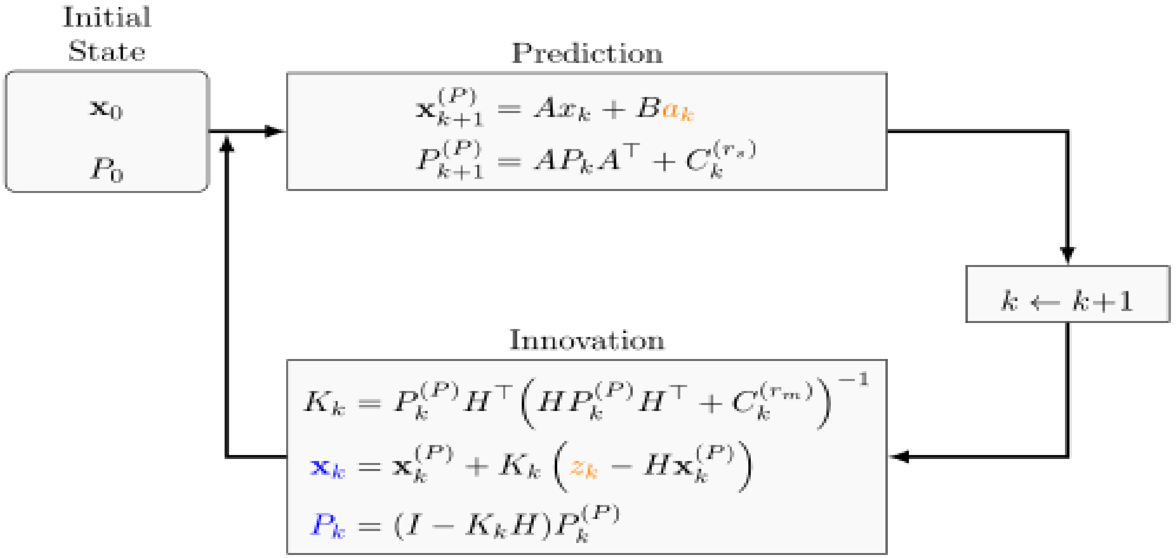


Fig. 1. Schematic structure of an accelerometer

Inertial navigation

- Kalman filter.
- Estimating states.

- Drift
  - Integrating error and measurement error.
  - Modelling errors of the system.



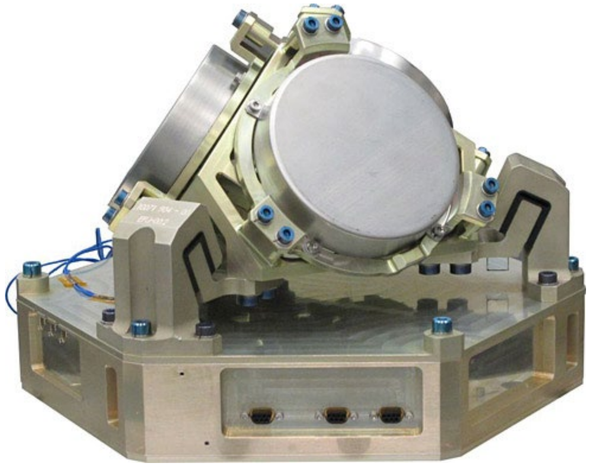
Inertial navigation systems

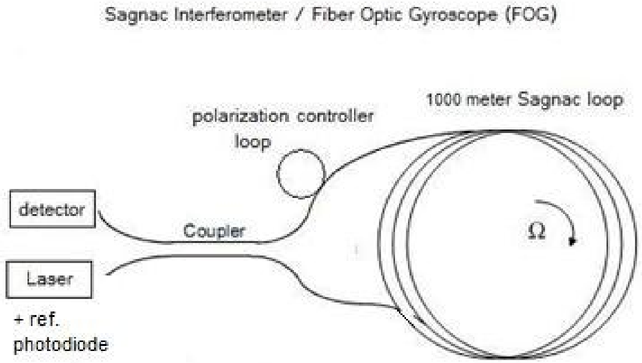
- instantaneous output of position and velocity
- completely self contained
- all weather global operation
- very accurate azimuth and vertical vector measurement
- error characteristics are known and can be modelled quite well
- works well in hybrid systems

- Position/velocity information degrade with time (1-2NM/hour).
- Equipment is expensive ($250,000/system)
- Initial alignment is necessary

Inertial measurement unit (IMU)

- Sensors:
  - 3 accelerometers
  - 3 gyroscopes
  - True North
- Issues:
  - Bias
  - Scale effects
- Gyro technologies
  - RLG
  - FOG
  - MEMS
  - Spinning mass





Combined system

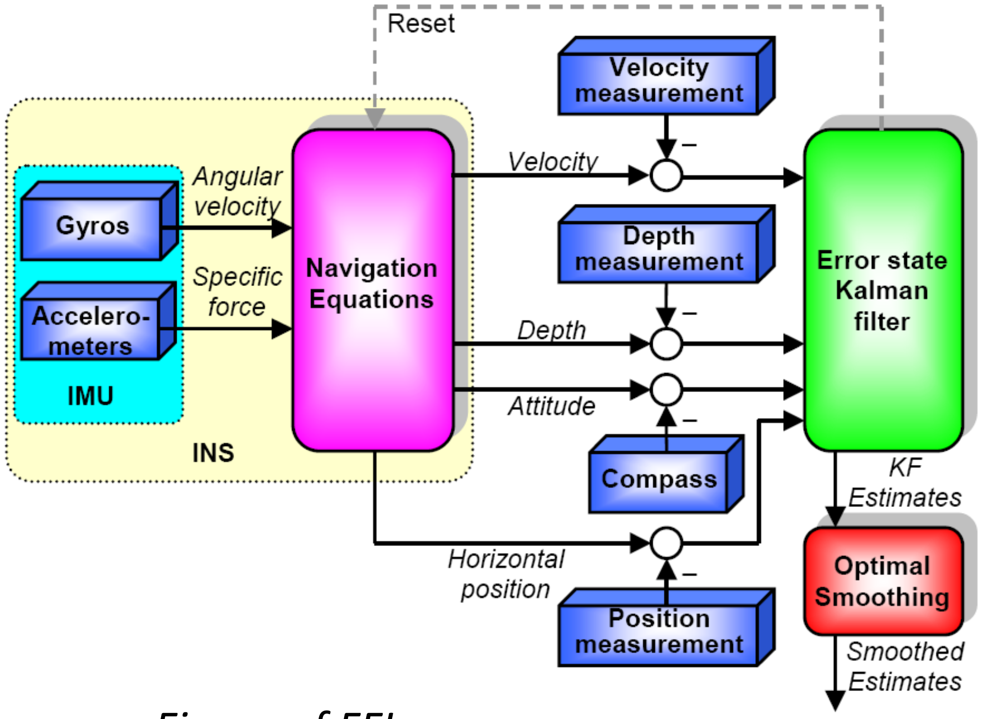


Figure of FFI

Example of dead reckoning navigation

Hegrenæs 2010

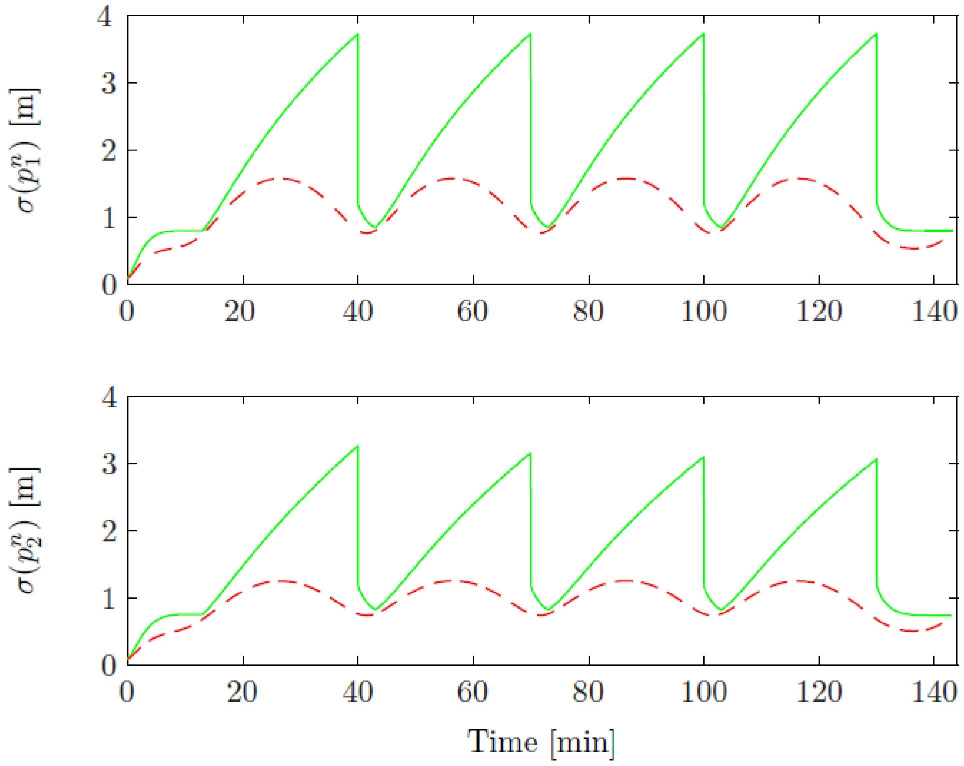


Fig. 5. Effectiveness of RTS smoothing. The estimated smoothed and real-time north and east position uncertainties (1σ) are shown in red (dashed) and green (solid), respectively. The data correspond to the 30 min case in Table V.

Examples from combined systems

Hegrenæs 2010

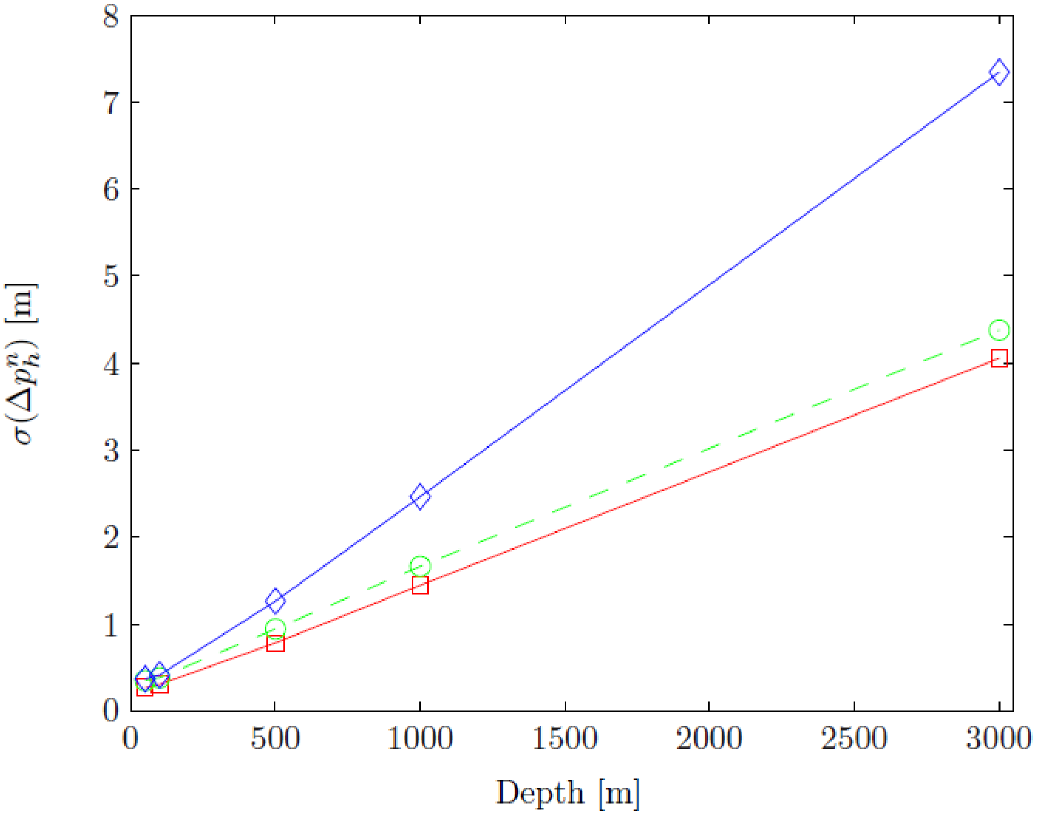


Fig. 9. Horizontal position uncertainty (1σ) for AUV AINS with GPS-HiPAP. The uncertainties are found from Table II–IV. Note that the values in Table I are not included since they are already embedded in Table IV. The real-time and smoothed uncertainties are shown as (○) and (□), respectively. For comparison the uncertainties for the complete GPS-HiPAP system are shown as (◇). The latter values are calculated based on Table I-III.

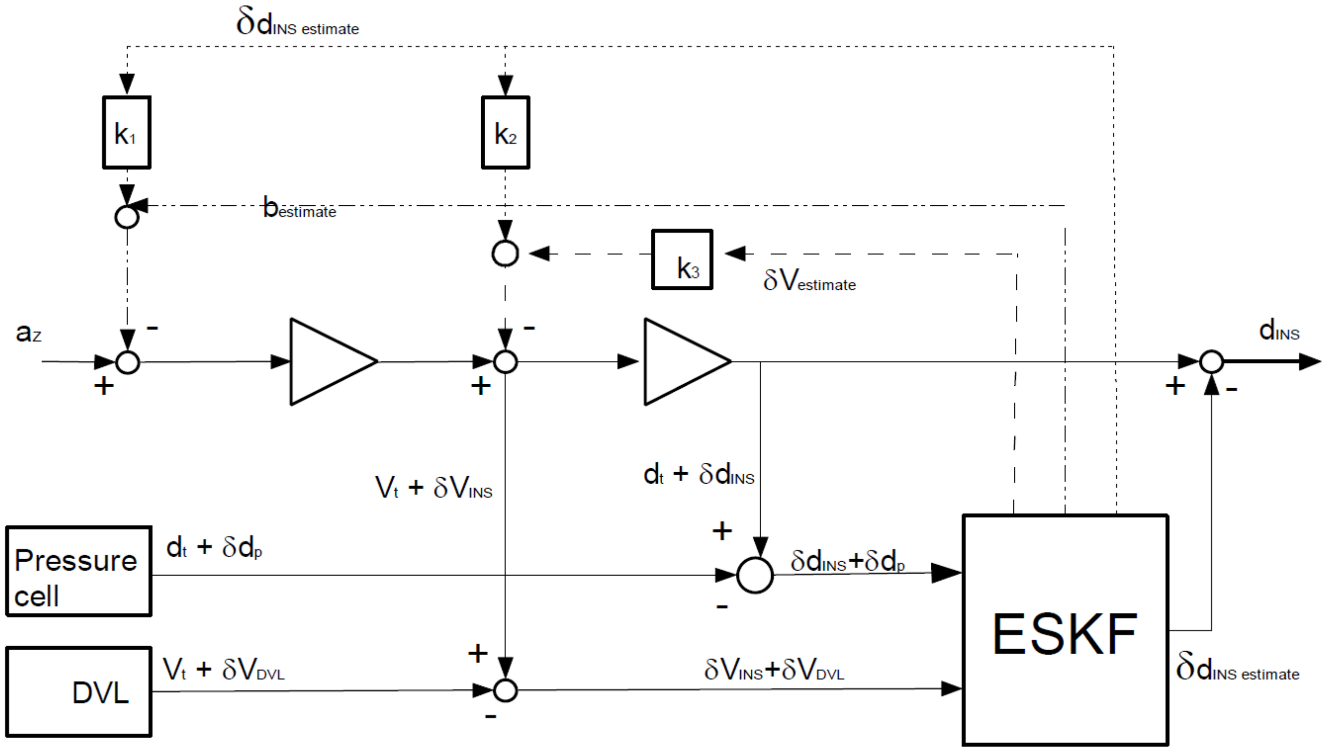
Typical requirements IHO

Table 4.7 Position requirements according to IHO S-44 (IHO 2008). *a* is the constant depth error, i.e. the sum of all errors, *b* denotes a factor dependent of depth and *d* is the depth.

S-44 PRECISON:	Special order	1 (a+b) order	2 order
Horizontal accuracy (95 % Confidence Level)	2 m	5 m + 5 % of depth	20 m + 5 % of depth
Depth Accuracy for Reduced Depths (95 % Confidence Level)	a = 0.25 m b = 0.0075	a = 0.5 m b = 0.013	a = 1.0 m b = 0.023

$$e = \pm\sqrt{a^2 + (b \cdot d)^2} \qquad (4.8)$$

Vertical channel mechanization



Vertical channel error sources

- Density
- Gravity
- Tide
- Atmospheric pressure

$$z = \int_{P_{\mathrm{ATM}}}^{P_{\mathrm{AUV}}} \frac{1}{\rho(S,t,p)\,g(L,p)}\,\mathrm{d}p,$$

Vertical channel - example

Table 4.1 *Calculations done for the mission in Skagerak 26th of September 2001. The errors associated with measured pressure of 600 dBar are corrected.*

	Magnitude Estimated	**MARPOS**	**Units**	**Measurement precision**	**Magnitude of error in cm**	**Relative error**
Gravity	9.817963	9.82	m/s^2	< 100μg	12.3	0.0205%
Density	1029.8760	1026	Kg/m^3	FSI CTD Man	224	0.3735%
Tide[5] Time:06:50-07:56	-36 –28	0	cm	1 cm	36 –28	0.06%
Atmospheric pressure Time: 06:00	1021.7	1013.0	hPa	N/A	8.58e-4	~ 0
Total error					**264.3 - 272.3**	

Summary sensors

Table 1. Commonly Used Underwater Vehicle Navigation Sensors

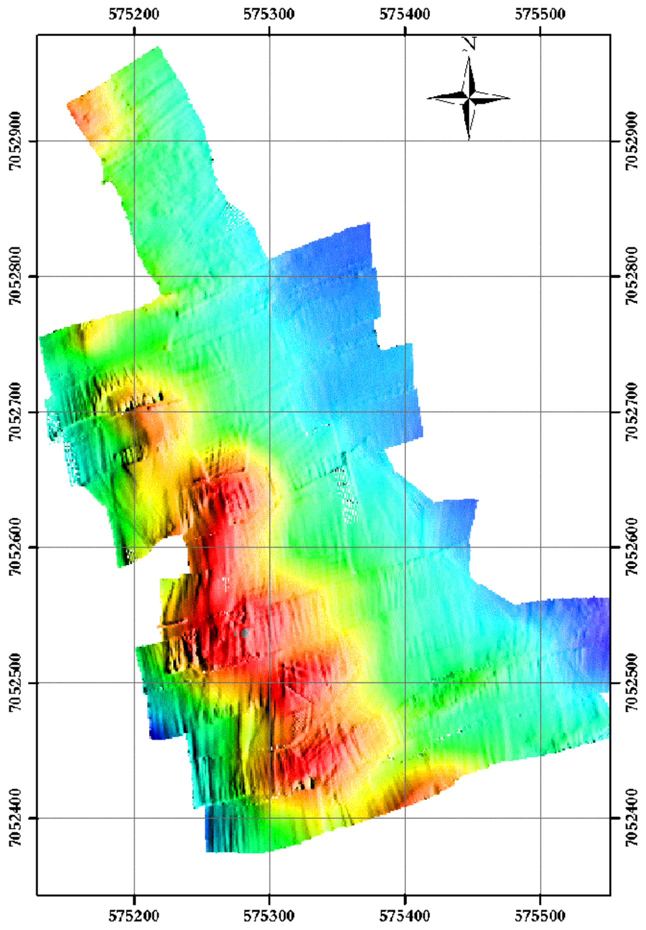
INSTRUMENT	VARIABLE	UPDATE RATE	PRECISION	RANGE	DRIFT
Acoustic Altimeter†	Z - Altitude	varies: 0.1-10Hz	0.01-1.0 m	varies with frequency	—
Pressure Sensor†	Z - Depth	medium: 1Hz	01% - .01%	full ocean depth	—
Inclinometer†	Roll, Pitch	fast: 1-10Hz	0.1° - 1°	$+/-45°$	—
Magnetic Compass†	Heading	fast: 1-10Hz	$1-10°$	360°	—
Gyro: (mechanical)†	Heading	fast: 1-10Hz	0.1°	360°	$10°/h$
Gyro: Ring-Laser and Fiber-optic†	Heading	fast: 1-1600Hz	0.1° - 0.01°	360°	$0.1-10°/h$
Gyro: North Seeking†	Heading, Pitch, Roll, $\ddot{x}$,ω	fast: 1-100Hz	0.1° - 0.01°	360°	—
12 kHz LBL	XYZ Position	varies: 0.1-1.0 Hz	0.1-10 m	5-10 Km	—
300 kHz LBL	XYZ Position	varies: 1.0-10.0 Hz	+/-0.007 m	100 m	—
IMU†	$\ddot{x}, \omega, \dot{\omega}$	fast: 1-1000Hz	0.01m	varies	varies
Bottom-Lock Doppler†	$\dot{x}_{body}$	fast:1-5Hz	0.3% or less	varies: 18 - 100 m	
Global Positioning System	XYZ Position	fast: 1-10 Hz	0.1-10 m in air	In water: 0 m	—

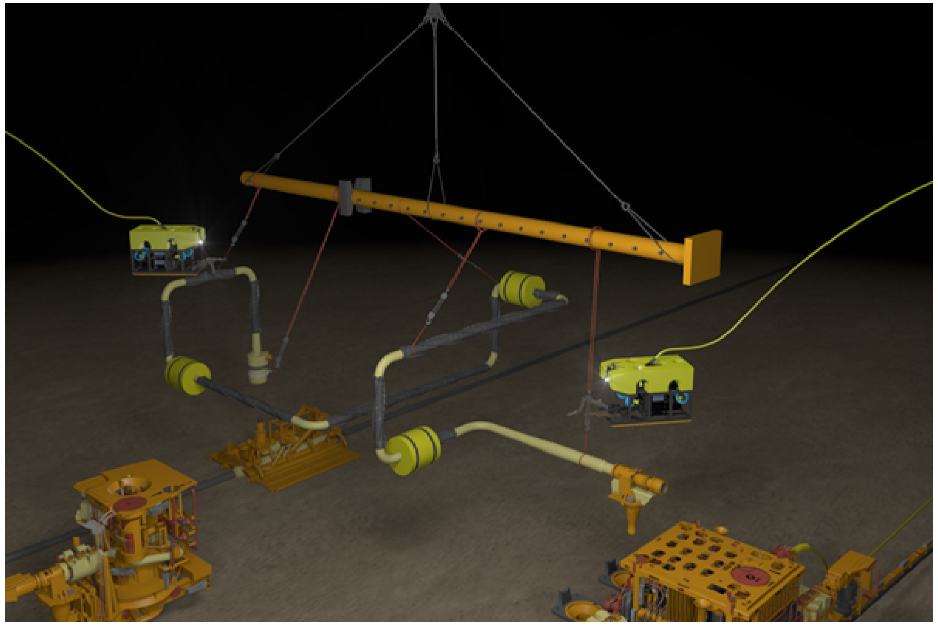
Kinsey et al 2006

Quality assessment

- Aiding
- Post processing
- Filtering

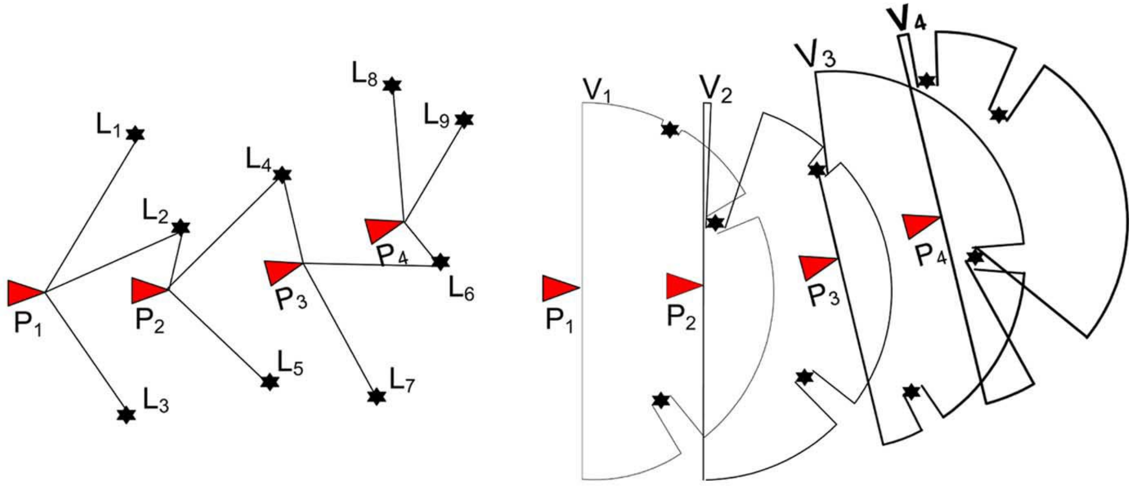
Navigation features of multibeam data





SLAM

- Simultaneous Localization And Navigation
- SLAM is a technique used to build up a map within an unknown environment or a known environment while at the same time keeping track of the current location.

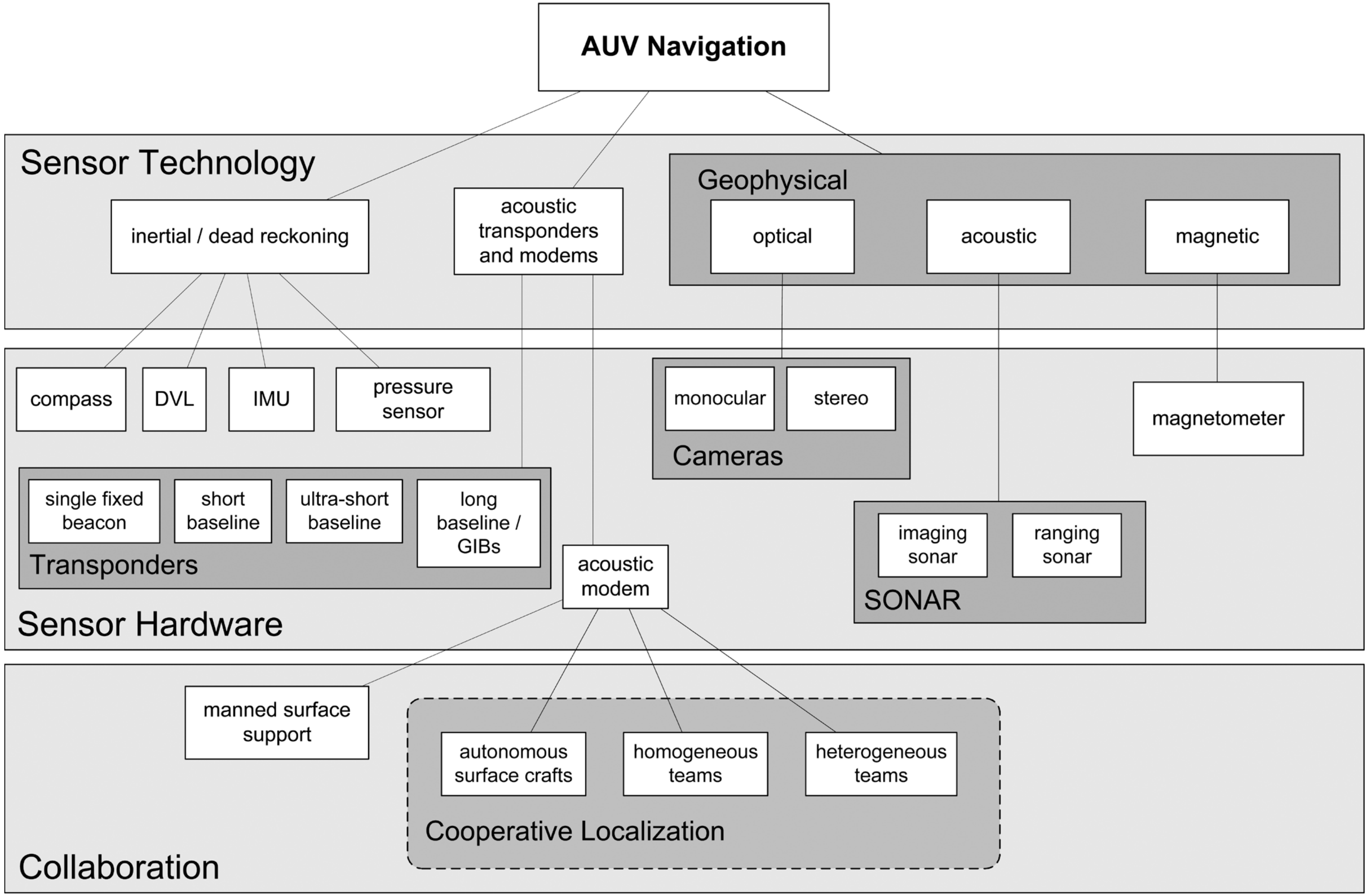


(a) (b)

SLAM

EKF SLAM		
SEIF SLAM	(Sparse Extended Information Filter)	
FastSLAM	(Particle Filter)	View based and feature based SLAM
GraphSLAM		Trajectory and map Offline
AI SLAM		

Classification of underwater navigation



Paull 2014

Learning objectives

- Kinematics and reference frames
- Concepts for navigation and positioning
  - Acoustic positioning
  - Dead reckoning
  - Inertial navigation
- Navigation instruments
- Error budgets

More reading

Positioning:

- Anonsen 2013
- Kebkal 2017

Navigation

- Gade 2016
- Hegrenes 2009