
Advanced Certificate in Subsea Robotics and AI

Subsea Navigation And Localization

Subsea navigation and localization constitute the backbone of autonomous operations beneath the ocean surface. In this detailed glossary, each term is defined, contextualized, and illustrated with practical examples that highlight its relevance to modern subsea robotics and artificial intelligence. The focus is on the terminology that engineers, researchers, and operators encounter when designing, deploying, and maintaining autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), and subsea inspection platforms. Understanding these terms enables clear communication across multidisciplinary teams and supports the development of robust navigation algorithms capable of handling the harsh and uncertain underwater environment.

Inertial Navigation System (INS) – An INS is a self-contained sensor suite that combines accelerometers and gyroscopes to estimate a vehicle's position, velocity, and orientation by integrating measured forces over time. Because it does not rely on external signals, an INS provides continuous navigation even when acoustic or optical references are unavailable. However, the integration process introduces drift, causing the error to grow proportionally to the square of time. In practice, an INS is often paired with other sensors in a sensor-fusion architecture to bound this drift.

Example: An AUV performing a long-duration pipeline inspection may start a mission with a known surface GPS fix. The INS then tracks the vehicle's motion throughout the dive, while periodic acoustic updates from a Long Baseline (LBL) network correct accumulated INS errors.

Doppler Velocity Log (DVL) – A DVL measures the vehicle's velocity relative to the seafloor or water column by emitting acoustic pulses and analyzing the Doppler shift of the reflected signals. The device typically uses four or more transducers arranged in a fan-shaped pattern to resolve three-dimensional velocity components. By integrating the DVL velocity over time, a dead-reckoning estimate of position can be obtained. The accuracy of a DVL is highly dependent on the reflectivity of the seafloor and the stability of the vehicle's altitude.

Practical usage: During a seabed mapping mission, the DVL provides high-frequency velocity updates (often at 10 Hz or higher) that feed directly into an Extended Kalman Filter (EKF) to improve pose estimation.

Ultra-Short Baseline (USBL) system – USBL is an acoustic positioning technology that determines the range and bearing of a transponder attached to the vehicle from a surface ship or a subsea beacon. The system consists of a small array of hydrophones (typically 3–4) mounted close together, which allows for a compact footprint on the host platform. USBL calculates the time-of-flight of acoustic pings and uses beamforming techniques to estimate the direction of arrival. Because the baseline is short, USBL offers rapid acquisition and is less susceptible to multipath interference than longer arrays, though its angular resolution is coarser

than that of a Long Baseline system.

Scenario: An ROV deployed from a vessel may rely on a USBL link for real-time position updates, enabling the operator to maintain situational awareness while conducting a subsea intervention.

Long Baseline (LBL) network – An LBL system employs a set of fixed acoustic beacons, typically anchored to the seafloor in a known geometric configuration (often a triangle or a square). The vehicle carries a transceiver that interrogates each beacon, measuring the round-trip travel time of acoustic signals. By solving the set of distance equations, the vehicle's three-dimensional position can be triangulated with high accuracy, often within a few centimeters. LBL is considered the gold standard for subsea positioning, especially for high-precision tasks such as pipeline burial or subsea construction.

Implementation note: Deploying an LBL network requires careful pre-mission planning to ensure beacon placement accounts for water depth, acoustic propagation characteristics, and potential obstacles that could shadow the acoustic paths.

Acoustic positioning – This umbrella term refers to any technique that derives position information from the propagation of sound waves through water. Acoustic positioning includes USBL, LBL, Short Baseline (SBL), and even one-way ranging methods. The speed of sound in seawater (approximately 1500 m/s, but variable with temperature, salinity, and pressure) is a critical parameter; inaccurate sound-speed estimates can cause systematic positioning errors.

Key challenge: The sound-speed profile (SSP) must be measured or modeled for each mission, often using a Conductivity-Temperature-Depth (CTD) sensor package, to calibrate acoustic ranging calculations.

Sonar (Sound Navigation and Ranging) – Sonar systems generate acoustic pulses and listen for echoes to detect objects, map the seafloor, or assist in navigation. Sonar can be active (emitting a pulse) or passive (listening only). Active sonar types include single-beam, multibeam, side-scan, and synthetic aperture sonar (SAS). Each variant provides different spatial resolutions and coverage patterns, influencing how the data can be used for localization.

Application example: An AUV equipped with a multibeam sonar can produce high-resolution bathymetric maps while simultaneously using the returned echoes to estimate its altitude above the seabed, feeding that information into a terrain-relative navigation algorithm.

Multibeam sonar – A multibeam system emits a fan of acoustic beams across a swath perpendicular to the vehicle's heading. By measuring the travel time and beam angle for each return, a dense point cloud of seafloor elevations is generated. The swath width is typically a function of the water depth; deeper waters yield broader coverage. Multibeam data can be processed to produce digital terrain models (DTMs), which serve as a reference for terrain-relative navigation (TRN).

Practical note: The accuracy of multibeam-derived altitude estimates depends on precise knowledge of the

vehicle's attitude (roll, pitch, yaw) and the sound-speed profile; errors in either can cause systematic bias in the terrain map.

Side-scan sonar – Side-scan sonar produces high-resolution images of the seafloor by sweeping acoustic beams laterally as the vehicle moves forward. Unlike multibeam sonar, side-scan does not provide absolute depth measurements; rather, it emphasizes the intensity of returned echoes, highlighting objects and textures. Side-scan data are valuable for detecting debris, wrecks, or other anomalies that may affect navigation safety.

Use case: During a debris-clearance mission, an ROV can rely on side-scan sonar to locate large objects that could entangle its manipulator arms, allowing the operator to plan avoidance maneuvers.

Simultaneous Localization and Mapping (SLAM) – SLAM is a computational framework that enables a vehicle to build a map of an unknown environment while concurrently estimating its own pose within that map. In the subsea context, SLAM algorithms often fuse sonar-derived features, inertial measurements, and acoustic ranging to maintain a consistent estimate of both map and trajectory. The nonlinear nature of underwater dynamics and the scarcity of distinctive visual landmarks make SLAM especially challenging underwater.

Algorithmic insight: A common approach is to use a factor graph representation, where each measurement (e.g., a DVL velocity, a USBL range) contributes a factor that constrains the vehicle's pose. Optimization techniques such as incremental smoothing and mapping (iSAM) can then be applied to produce a globally consistent solution.

Pose – Pose refers to the full six-degree-of-freedom (6-DOF) description of a vehicle's position (x, y, z) and orientation (roll, pitch, yaw). Pose is often expressed as a transformation matrix or a combination of a three-dimensional translation vector and a rotation representation (quaternion or Euler angles). Accurate pose estimation is essential for tasks such as manipulator control, sensor pointing, and collision avoidance.

Example: A manipulator arm mounted on an AUV must know the vehicle's pose with sub-centimeter and sub-degree accuracy to successfully attach a connector to a subsea valve.

Orientation representation – Two common ways to encode orientation are Euler angles and quaternions. Euler angles are intuitive (roll, pitch, yaw) but suffer from singularities (gimbal lock) and can be ambiguous near $\pm 90^\circ$ pitch. Quaternions avoid these singularities and provide smooth interpolation, making them preferred for real-time navigation filters.

Implementation tip: When integrating gyroscope data, convert angular velocity to quaternion increments to maintain numerical stability over long missions.

Dead Reckoning (DR) – Dead reckoning is a navigation method that estimates current position by extrapolating from a known past position using measured velocities and heading changes. In subsea

applications, DR typically combines INS data with DVL velocity to produce a short-term position estimate. Because DR does not incorporate external corrections, its error grows unboundedly, making it suitable only for limited time intervals between absolute fixes.

Practical scenario: An AUV may rely on DR while traversing a featureless sand flat where acoustic ranging is unreliable, then re-anchor its estimate using a brief USBL ping when the vehicle surfaces to a known depth.

Sensor fusion – Sensor fusion is the process of combining measurements from heterogeneous sensors to produce a more accurate and robust estimate of the vehicle's state than any single sensor could provide. Fusion techniques range from simple weighted averages to sophisticated Bayesian filters. In subsea navigation, typical fusion pipelines integrate INS, DVL, acoustic ranging, depth sensors, and occasionally visual or magnetic cues.

Common filter: The Extended Kalman Filter (EKF) linearizes the system dynamics around the current estimate, allowing for real-time updates while handling nonlinear measurement models such as acoustic range equations.

Kalman filter (KF) – The Kalman filter is an optimal estimator for linear Gaussian systems. It recursively predicts the system state using a motion model and corrects the prediction with sensor measurements, weighting each according to its covariance. While the classic KF assumes linear dynamics, many subsea navigation problems require extensions.

Key point: The filter's performance hinges on correctly modeling process noise (e.g., vehicle thrust variations) and measurement noise (e.g., acoustic ranging uncertainty).

Extended Kalman Filter (EKF) – The EKF extends the Kalman filter to handle nonlinear system dynamics by linearizing the motion and measurement models around the current state estimate at each step. This approach is widely used in underwater navigation because the relationship between acoustic ranges and vehicle position is inherently nonlinear.

Example: When incorporating a USBM (Ultra-Short Baseline) range measurement, the EKF computes the Jacobian of the range equation with respect to the vehicle's position to appropriately update the covariance matrix.

Unscented Kalman Filter (UKF) – The UKF addresses some limitations of the EKF by propagating a set of deterministic sigma points through the nonlinear functions, capturing higher-order moments without explicit linearization. The UKF can provide more accurate estimates when the system exhibits strong nonlinearity, such as during rapid vehicle maneuvers or when the acoustic geometry is highly distorted.

When to choose: If an AUV frequently executes aggressive turns in a confined harbor, the UKF may yield better localization performance than an EKF.

Particle filter (PF) – A particle filter represents the posterior distribution of the vehicle's state using a set of

weighted random samples (particles). PFs can model multimodal distributions, making them suitable for ambiguous environments where multiple pose hypotheses exist (e.g., when acoustic measurements are intermittent). However, PFs are computationally intensive, especially in high-dimensional state spaces.

Application: A deep-sea glider that experiences long periods of GPS denial may employ a particle filter to maintain a set of plausible trajectories until a surfacing fix becomes available.

Acoustic modem – Acoustic modems enable bidirectional data communication between underwater platforms and surface stations. They modulate data onto acoustic carriers, using techniques such as frequency-shift keying (FSK) or phase-shift keying (PSK). Bandwidth is limited (typically a few kilobits per second), and latency can be high due to the low speed of sound.

Use case: During a long-duration mission, an AUV may transmit compressed sonar mosaics via an acoustic modem to a surface vessel for real-time monitoring, while receiving updated waypoints based on recent acoustic positioning.

Conductivity-Temperature-Depth (CTD) sensor – The CTD measures the water's conductivity, temperature, and pressure, from which salinity and sound-speed profiles can be derived. Accurate SSP information is essential for correcting acoustic ranging errors, as the speed of sound can vary by several meters per second over a 100 m depth change.

Operational tip: Deploy a CTD near the vehicle's path at regular intervals to capture temporal variations in temperature layers that could affect acoustic propagation.

Sound-speed profile (SSP) – The SSP describes how the speed of sound varies with depth, temperature, salinity, and pressure. It is typically represented as a piecewise linear or spline function. Inaccurate SSP modeling leads to systematic range errors, especially for long-baseline acoustic positioning where the acoustic path traverses multiple thermoclines.

Mitigation strategy: Perform an in-situ SSP measurement before each mission and update the acoustic navigation filter with the latest profile.

Reference frame – A reference frame defines a coordinate system in which positions and orientations are expressed. Common frames in subsea navigation include the Earth-Centered Earth-Fixed (ECEF) frame, the North-East-Down (NED) local tangent frame, and the vehicle-body frame. Transformations between frames must be handled consistently to avoid navigation inconsistencies.

Example: GPS coordinates obtained at the surface are expressed in the ECEF frame, while DVL velocities are naturally reported in the vehicle-body frame; both must be transformed into a common NED frame for fusion.

Coordinate system – The coordinate system is the set of axes that define a reference frame. In underwater navigation, a right-handed NED system is standard: X points north, Y points east, and Z points down

(positive depth).

Note: Some legacy sonar manufacturers use a left-handed system; careful conversion is required when integrating data from multiple sources.

Transformation matrix – A 4×4 homogeneous matrix that encodes rotation and translation between coordinate frames. It is widely used in robotics to concatenate multiple pose transformations (e.g., sensor offsets, vehicle attitude).

Practical tip: Store the transformation from the DVL sensor frame to the vehicle body frame as a constant matrix, and apply it each time a new DVL velocity reading is received.

Quaternion – A four-component representation (w, x, y, z) of rotation that avoids singularities and provides efficient composition. Quaternions are normalized to unit length to represent pure rotations.

Implementation hint: When updating the EKF state with gyroscope integration, use the quaternion multiplication rule to propagate orientation.

Euler angles – Three angles representing sequential rotations about the axes of a coordinate frame (commonly roll, pitch, yaw). While intuitive, Euler angles suffer from gimbal lock when the pitch approaches $\pm 90^\circ$, leading to numerical instability.

Best practice: Convert Euler angles to quaternions for filter propagation, and only convert back to Euler for human-readable display.

Depth sensor – Devices that measure the vehicle's vertical position relative to the sea surface. Depth can be obtained from a pressure transducer calibrated to convert pressure to depth, often corrected for seawater density. Depth sensors provide a reliable measurement of the Z coordinate, which is valuable for constraining vertical drift in navigation filters.

Example: An AUV operating near a known seafloor depth can use a high-precision pressure sensor to maintain altitude within ± 0.1 m, enhancing the reliability of DVL-based velocity integration.

Altitude sensor – Sensors that measure the distance from the vehicle to the seafloor. Common implementations include short-range acoustic ranging (e.g., a narrow-beam altimeter) or sonar-derived altitude from multibeam swaths. Altitude data are crucial for terrain-relative navigation and for preventing collisions with the seabed.

Use case: A mining robot uses a forward-looking altimeter to maintain a constant standoff distance while scraping mineral deposits from the seafloor.

Terrain-Relative Navigation (TRN) – TRN leverages a pre-existing bathymetric map to estimate vehicle pose by matching real-time sonar observations to the map. By aligning observed features (e.g., ridges,

depressions) with known terrain, the vehicle can correct drift without requiring active acoustic beacons. TRN is especially valuable in GPS-denied environments where deploying a full LBL network is impractical.

Algorithmic approach: A common TRN method uses a Monte-Carlo localization scheme, where each particle proposes a pose hypothesis, and a likelihood function evaluates the match between the observed sonar scan and the stored map.

Bathymetric map – A digital representation of seafloor topography, typically stored as a grid of depth values (e.g., a raster DEM). Bathymetric maps can be generated from prior multibeam surveys, satellite altimetry, or historical sonar data. The map resolution (grid spacing) determines the level of detail available for terrain matching.

Practical consideration: When using a bathymetric map for TRN, ensure the map's datum matches the vehicle's reference frame to avoid systematic offsets.

Map matching – The process of aligning sensor observations with a stored map to infer the vehicle's pose. In underwater navigation, map matching often involves correlating sonar intensity patterns with the bathymetric model. Techniques such as normalized cross-correlation, mutual information, or feature extraction (e.g., ridge detection) are employed.

Example: An AUV navigating a canyon may extract the canyon walls as high-gradient features and compare them to the stored map, yielding a pose correction that reduces lateral drift.

Loop closure – In SLAM, loop closure refers to the detection that the vehicle has returned to a previously visited location. Recognizing a loop allows the algorithm to reconcile accumulated pose errors by adjusting the map and trajectory to maintain global consistency. Loop closure detection underwater is challenging due to the limited distinctiveness of terrain; however, sonar-based place recognition methods can be employed.

Method: A bag-of-words approach can be applied to side-scan sonar patches, enabling the system to recognize previously observed seafloor textures despite changes in vehicle heading.

Feature extraction – The process of identifying salient points or patterns in sensor data that can be used for matching or tracking. In subsea sonar, features may include edges of ridges, corners of man-made structures, or texture patches with high variance. Feature descriptors (e.g., SIFT, SURF) can be adapted for acoustic imagery, though the lower resolution and speckle noise of sonar require robust preprocessing.

Practical tip: Apply median filtering to side-scan images before extracting features to suppress speckle while preserving structural edges.

Speckle noise – A granular interference pattern inherent to coherent imaging systems such as sonar. Speckle arises from the constructive and destructive interference of scattered acoustic waves and can obscure fine details.

Mitigation: Adaptive filtering (e.g., Lee filter) and multi-look averaging can reduce speckle, improving the reliability of feature extraction for navigation purposes.

Acoustic multipath – Multipath occurs when an acoustic signal reflects off multiple surfaces (e.g., sea surface, seafloor, or sidewalls) before reaching the receiver, creating delayed copies of the original pulse. Multipath can cause ranging errors, false detections, and degrade the performance of acoustic modems.

Example: In shallow water, a USBL system may receive a direct path and a surface-reflected path, leading to ambiguous range estimates unless the filter accounts for the extra travel time.

Acoustic shadowing – Shadowing refers to regions where acoustic signals are blocked or severely attenuated by obstacles such as large structures, cliffs, or dense vegetation. Shadow zones reduce the reliability of acoustic ranging and sonar imaging.

Mitigation strategy: Deploy additional beacons or reposition the vehicle to obtain line-of-sight to the target, or use alternative sensors (e.g., inertial) when acoustic coverage is insufficient.

Magnetic interference – Subsea platforms often carry ferromagnetic components (e.g., thrusters, steel frames) that generate local magnetic fields, contaminating magnetometer readings. Magnetometer data are sometimes used to aid heading estimation, but interference must be modeled or filtered.

Practical approach: Perform a magnetic calibration on the vehicle prior to deployment, and apply a hard-iron/soft-iron compensation algorithm to correct raw magnetometer outputs.

Water currents – Ocean currents exert forces on the vehicle, causing drift that is not captured by dead-reckoning sensors. Current estimation can be incorporated into navigation filters as a bias term or modeled separately using an oceanographic model.

Example: An AUV operating in a strong tidal stream may experience lateral drift of several meters per minute; integrating a current estimate from an ADCP (Acoustic Doppler Current Profiler) can improve positional accuracy.

Acoustic Doppler Current Profiler (ADCP) – An ADCP measures water velocity profiles by emitting acoustic beams at known angles and analyzing the Doppler shift of backscattered particles. By providing a vertical profile of current speed and direction, the ADCP enables the navigation system to compensate for current-induced drift.

Application: When traversing a canyon, an AUV can use ADCP data to predict the lateral displacement caused by the stratified flow and adjust its heading accordingly.

Thruster dynamics – The relationship between commanded thrust and actual vehicle motion is affected by factors such as propeller slip, buoyancy changes, and nonlinear hydrodynamic forces. Accurate modeling of thruster dynamics is essential for predictive control and for reducing navigation error during aggressive

maneuvers.

Modeling tip: Use a first-order lag model with a gain and time constant calibrated on-board to capture the response of each thruster to PWM commands.

Hydrodynamic drag – Drag forces oppose vehicle motion and are proportional to the square of the relative speed through water, modulated by the vehicle's shape and surface roughness. Drag contributes to the process noise in navigation filters, especially when the vehicle accelerates or decelerates rapidly.

Practical consideration: Include a drag term in the motion model of the EKF to better predict velocity changes between DVL updates.

State vector – In a navigation filter, the state vector encapsulates all variables to be estimated, typically including position, velocity, orientation, sensor biases, and sometimes environmental parameters such as current velocity.

Example: A 15-dimensional EKF state for an AUV might consist of (x, y, z, vx, vy, vz, quaternion, gyro bias, accelerometer bias, DVL bias, water-current velocity).

Process noise – Process noise captures the uncertainty in the system's dynamics, representing unmodeled effects such as thruster jitter, hydrodynamic variations, or sensor drift. Properly tuning process noise covariance matrices is crucial for filter stability.

Guideline: Start with conservative (large) process noise values to avoid filter divergence, then iteratively reduce them based on observed residuals.

Measurement noise – Measurement noise quantifies the uncertainty associated with each sensor reading. It is represented as a covariance matrix in the filter update step. Accurate characterization of measurement noise improves filter weighting and convergence.

Example: A DVL's velocity measurement noise may be modeled as a diagonal matrix with 0.02 m/s variance per axis, reflecting the manufacturer's specifications.

Covariance matrix – The covariance matrix encodes the estimated uncertainty of the state vector and the cross-correlations between its components. In the EKF, the covariance matrix is propagated forward in the prediction step and reduced in the update step as new measurements arrive.

Interpretation: A large diagonal entry for the depth variable indicates high uncertainty in the vertical position, prompting the filter to rely more heavily on a depth sensor when it becomes available.

Outlier detection – Outlier detection identifies measurements that deviate significantly from the expected model, which could be caused by sensor glitches, multipath, or environmental disturbances. Robust filters often reject outliers to prevent corruption of the state estimate.

Technique: Apply a chi-square test on the innovation (measurement residual) and reject any measurement whose normalized residual exceeds a chosen threshold (e.g., 95 % confidence).

Innovation (residual) – The innovation is the difference between the actual sensor measurement and the predicted measurement based on the current state estimate. It serves as a feedback signal for the filter update.

Interpretation: A large innovation in a USBL range may indicate a temporary acoustic shadow or a mis-configured sound-speed profile.

Batch optimization – Unlike real-time filters, batch optimization processes all collected measurements simultaneously to produce a globally optimal trajectory and map. Techniques such as bundle adjustment or graph-based SLAM fall into this category.

When to use: After a long-duration survey, post-process the data offline to refine the vehicle's trajectory, reducing accumulated drift beyond what real-time filters could achieve.

Graph-based SLAM – In graph-based SLAM, each pose is represented as a node, and each measurement (e.g., a DVL integration, an acoustic range) forms an edge linking two nodes. Optimization algorithms (e.g., Gauss-Newton) adjust node positions to minimize the total error across all edges.

Benefit: Graph-based SLAM naturally accommodates loop closures, allowing the system to redistribute error across the entire trajectory.

Bundle adjustment – A specific form of batch optimization that jointly refines camera (or sonar) poses and observed feature locations to minimize reprojection error. In underwater SLAM, bundle adjustment can be applied to sonar image mosaics, aligning overlapping scans into a coherent map.

Application: An AUV collecting side-scan mosaics can run bundle adjustment offline to produce a seamless seafloor image with accurate georeferencing.

Real-time kinematic (RTK) GPS – While RTK GPS is not directly usable underwater, surface vessels equipped with RTK can provide highly accurate position references for acoustic positioning systems. The surface reference improves the absolute accuracy of USBL or LBL fixes.

Example: A support ship maintains an RTK-corrected position, which is then used as the origin for an LBL network, ensuring that all subsea beacons share a centimeter-level reference.

Surface vessel tracking – Tracking the surface vessel's motion is essential for converting relative acoustic measurements (e.g., USBL ranges) into absolute positions. The vessel's navigation system typically supplies GPS position, heading, and velocity, which are fed into the subsea filter as known quantities.

Practical tip: Synchronize the vessel's clock with the vehicle's clock using a network time protocol (NTP) to

avoid timing mismatches that could corrupt range calculations.

Time synchronization – Accurate time stamps are vital for correlating sensor data, especially when combining high-frequency inertial measurements with lower-frequency acoustic updates. Errors in synchronization can manifest as apparent position jumps or inaccurate velocity estimates.

Method: Use a Precision Time Protocol (PTP) over Ethernet when possible, or embed a GPS time pulse into the vehicle's data stream to maintain alignment.

Data logging – Comprehensive logging of raw sensor data, timestamps, and navigation filter states is indispensable for post-mission analysis, debugging, and algorithm improvement. Logs should be stored in a lossless format and include sufficient metadata (e.g., sensor calibration parameters).

Best practice: Record both raw and pre-processed data streams, allowing offline re-processing with updated filters or alternative algorithms.

Calibration – Calibration procedures adjust sensor parameters to match known references, reducing systematic biases. Calibration may involve static tests (e.g., placing the vehicle on a level surface to zero accelerometer bias) or dynamic maneuvers (e.g., rotating the vehicle to calibrate gyroscope scale factors).

Example: A four-point calibration of the DVL's mounting offset can be performed on-deck by rotating the vehicle in a known pattern and measuring the resulting velocity vectors.

Static alignment – The process of determining the rotational offset between sensor frames when the vehicle is stationary. By measuring the accelerometer output under gravity, the roll and pitch of the sensor can be inferred, aligning the vehicle-body frame with the inertial frame.

Implementation: Record a few seconds of static data after launch, compute the mean accelerometer vector, and derive the roll and pitch angles that align this vector with the gravity direction.

Dynamic alignment – Aligning sensor axes during motion, often using known vehicle maneuvers. Dynamic alignment can refine gyroscope scale factors and cross-axis sensitivities.

Procedure: Execute a series of constant-rate turns about each principal axis and compare the measured angular rates to the commanded rates, adjusting the gyroscope calibration matrix accordingly.

Bias estimation – In navigation filters, bias terms (e.g., gyro bias, accelerometer bias) are often added to the state vector and estimated online. By modeling bias as a slowly varying random walk, the filter can correct for sensor drift over long missions.

Example: An EKF with a bias term for each gyroscope axis can reduce heading drift from several degrees per hour to sub-degree levels over a 12-hour mission.

Environmental modeling – Incorporating knowledge of the surrounding environment (e.g., bathymetry,

current fields, temperature layers) into the navigation system can improve accuracy. Environmental models can be pre-loaded or updated in real time using onboard sensors.

Use case: A subsea inspection robot operating near a thermocline may adjust its acoustic ranging model based on a temperature sensor reading, reducing range error caused by abrupt sound-speed changes.

Adaptive filtering – Adaptive filters adjust their parameters (e.g., noise covariances) on the fly based on observed sensor performance. This adaptability helps maintain filter robustness when sensor quality varies, such as during acoustic shadowing or when the vehicle enters a turbulent region.

Technique: Monitor the innovation covariance; if it consistently exceeds the predicted value, inflate the measurement noise for that sensor until the residuals align with expectations.

Robust estimation – Robust estimation techniques mitigate the influence of outliers by using loss functions less sensitive to large residuals (e.g., Huber loss) or by employing RANSAC-style consensus methods.

Application: When processing a set of USBL ranges, a robust estimator can down-weight a few erroneous measurements caused by multipath, preserving overall trajectory integrity.

Monte-Carlo localization – A particle-filter-based approach that represents the posterior distribution of vehicle pose with a set of weighted samples. Monte-Carlo methods are well-suited for highly non-linear, multi-modal problems such as ambiguous acoustic measurements in feature-poor environments.

Example: A glider performing a long drift under weak currents can maintain a cloud of position hypotheses until a surfacing GPS fix collapses the distribution.

Feature-based matching – Matching discrete features extracted from sonar images to a prior map, rather than aligning entire intensity fields. Feature-based methods reduce computational load and can be more resilient to illumination changes (e.g., varying acoustic backscatter strength).

Technique: Detect corner-like structures using a Harris-type detector on side-scan sonar, then compute a descriptor based on local intensity gradients for matching.

Intensity-based matching – Aligning whole sonar scans by minimizing the difference in intensity values across the entire image. This approach can be more accurate when the environment contains abundant texture but is computationally intensive.

Algorithm: Use a gradient descent optimizer to find the translation and rotation that best aligns a current multibeam swath with the stored bathymetric raster.

Georeferencing – Assigning geographic coordinates (latitude, longitude, depth) to sensor data. Accurate georeferencing requires a precise transformation chain from the vehicle's local frame to the Earth-fixed frame, accounting for all sensor offsets and timing delays.

Practice: Store the transformation from the DVL frame to the vehicle body, the vehicle body to the NED frame, and finally the NED frame to the ECEF frame, applying each in sequence to convert raw ranges to global coordinates.

Coordinate transformation chain – The ordered sequence of rotations and translations that map measurements from sensor frames to a common reference frame. Errors in any link of the chain propagate downstream, potentially degrading navigation accuracy.

Example: A sonar beam vector expressed in the sonar frame must be rotated by the sonar-to-body matrix, then by the body-to-NED matrix, before being projected onto the global map.

Survey planning – The process of designing a mission trajectory that satisfies coverage, resolution, and navigation requirements. Effective planning incorporates knowledge of acoustic coverage, vehicle endurance, and environmental constraints.

Consideration: When planning a high-resolution bathymetric survey, ensure sufficient overlap between adjacent swaths (typically 20-30%) to support later SLAM or map-matching algorithms.

Mission execution monitoring – Real-time monitoring of navigation performance, sensor health, and environmental conditions during a mission. Operators track key metrics such as position error estimates, DVL lock status, and acoustic link quality to intervene if necessary.

Tool: A dashboard displaying the EKF covariance trace, DVL velocity magnitude, and USBL range residuals provides a quick health check for the navigation system.

Post-mission analysis – After a dive, data are examined to assess navigation accuracy, identify failure modes, and refine models. Analysts may reprocess the data with updated filters, compare estimated trajectories against ground truth (e.g., LBL fixes), and generate error