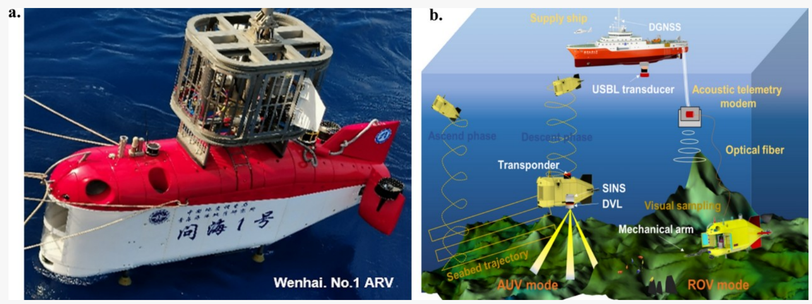
In-situ sound speed modelling makes underwater navigation smarter and more precise

GA, UNITED STATES, December 20, 2025 /EINPresswire.com/ -- Precise underwater navigation is critical for autonomous and remotely operated deep-sea vehicles, yet variations in seawater sound speed often introduce systematic acoustic positioning errors. This study presents an in-situ sound speed profile (SSP) correction scheme designed to improve Strap-down Inertial Navigation System (SINS) and Ultra-Short Baseline (USBL) integration. Using acoustic ray-tracing theory, the method links sound speed disturbances to positioning deviations, and incorporates an adaptive two-stage information filter to estimate SSP variations while detecting USBL outliers in real time. Simulations and sea trials demonstrate notable improvements in positional accuracy, enabling more stable navigation in variable ocean environments and supporting high-precision deep-sea surveys.



Wenhai No.1 ARV and experimental devices. a depicts the hybrid underwater vehicle of Wenhai No.1 ARV. b represents the general overview of Wenhai No.1 ARV navigation and measuring sensors.

Underwater navigation commonly relies on Strap-down Inertial Navigation System (SINS) / Ultra-Short Baseline (USBL) fusion because satellite signals cannot penetrate seawater. However, navigation precision decreases with depth and distance due to non-uniform sound speed, which changes with temperature, salinity, and pressure across time and depth. Pre-measured sound speed profiles serve as initial references, but long-endurance missions experience temporal sound speed profile (SSP) drift, causing refraction-induced travel-time and angle errors that accumulate in navigation results. Traditional correction relies on static conductivity-temperature-depth (CTD) profiler measurements or empirical models that fail to adapt to real-time conditions. Due to these problems, research is needed to dynamically estimate sound speed variation and compensate acoustic positioning distortion during deep-sea missions.

Researchers from and collaborating institutions reported a new real-time SSP correction scheme for tightly coupled SINS/USBL navigation, published in Satellite Navigation in 2025. The method models temporal SSP variability using acoustic ray-tracing and applies an adaptive two-stage information filter to jointly estimate sound speed disturbance and identify USBL outliers. Verified by simulations and South China Sea field experiments, the approach significantly reduces navigation error and supports reliable deep-sea operations.

The work begins by analyzing how time-varying SSP affects USBL acoustic propagation, altering ray incident angles and travel time. Based on Snell's law, the team derived partial differential relationships between sound-speed disturbance and horizontal/vertical displacements. A quasi-observation model was constructed, enabling estimation of SSP perturbation through differences between SINS-derived and USBL-measured travel time. A two-order SSP disturbance representation separates the shallow-water mixed layer, the thermocline transition zone, and the deep isothermal layer, reflecting realistic sound-speed distribution with depth. To fuse navigation data, the researchers designed an Adaptive Two-stage Information (ATI) filter combining SINS, Doppler Velocity Log (DVL), Pressure Gauge (PG) and USBL observations. The filter updates position, velocity and attitude errors while simultaneously detecting USBL anomalies through a Generalized Likelihood Ratio test and refining SSP estimation via recursive least squares. Simulations using MVP-collected CTD datasets showed that, without SSP correction, USBL horizontal positioning errors reached several meters. With the proposed algorithm, RMS error dropped markedly. Sea trials showed RMS position improved from 0.45 m to 0.08 m northward and 0.23 m to 0.07 m eastward—enhancing precision by over 80% under real mission conditions.

According to the authors, real-time SSP reconstruction is crucial for addressing navigation drift in deep-sea acoustic systems. "Traditional navigation often depends on static sound speed profiles, which quickly become outdated during long missions. Our model integrates physical ray-tracing with adaptive filtering, enabling ARVs to sense and correct sound-speed changes rather than rely on fixed inputs," the team noted. They believe the approach will support deep-ocean mapping, sampling, and seabed resource detection where precise localization is required under dynamic environmental conditions.

This SSP correction framework provides a practical path toward self-adaptive deep-sea navigation systems. By reducing dependence on external CTD surveys and improving resilience to acoustic distortion, it enhances navigation robustness during long deployments. The method is well-suited for autonomous remotely operated vehicle (ARVs) and Autonomous Underwater Vehicle (AUVs) performing seabed mapping, ecological monitoring, mineral exploration, under-ice routing, or long-range autonomous missions. Further developments could integrate machine-learning-based SSP prediction or multi-sensor oceanographic data for proactive correction. The authors foresee its potential to improve efficiency and data reliability in future deep-sea exploration and marine resource assessment.

References

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