SUPPLEMENTARY MATERIALS FOR

ADVANCING MONITORING OF NEARSHORE ANTARCTIC SEA ICE AND BENTHIC ECOSYSTEMS WITH HIcyBot

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TECHNICAL CHALLENGES OF UNDER-ICE HYPERSPECTRAL IMAGE GEOREFERENCING AND TIMESTAMPING

Pushbroom hyperspectral sensors, as used in this study, capture one line of spectral data at a time while the platform moves forward. This scanning process generates large datasets structured as hyperspectral cubes (X, Y, λ; see Figure 1 of the main article). Unlike frame-based imaging systems, pushbroom sensors require tight synchronization between each line acquisition and high-frequency navigation data to produce georeferenced images. This demands accurate timestamping of platform position and orientation (pitch, roll, and yaw), often at rates of up to 100 Hz. While challenging in terrestrial remote-sensing applications, this requirement is considerably more complex in underwater environments due to the absence of Global Navigation Satellite System (GNSS) signals. Any variation in scanning speed, or changes in platform attitude or orientation, can introduce geometric distortions into the imagery. Correcting these distortions typically requires advanced post-processing techniques such as motion compensation, sensor fusion, and time-based interpolation, many of which are still in development for aquatic environments.

Due to the natural nadir stabilization of the HIcyBot system and the relatively calm conditions during deployment, the need for intensive correction was greatly reduced in the presented datasets. Nonetheless, the system aims to integrate timestamped ultra-short baseline (USBL) acoustic positioning data with the imagery taken at high frequency. The Subsonos USBL system calculates position and heading by transmitting signals between a surface unit and a submerged receiver, removing the need for an external gyrocompass.

For this proof-of-concept, we implemented an ad hoc preprocessing approach to demonstrate frame, position, and attitude synchronization for underwater hyperspectral imaging (UHI) georeferencing. With eight hydrophones, a sound-speed sensor, and an internal inertial navigation system (INS) providing six-degree-of-freedom tracking, a complete set of navigation data is synchronized with the hyperspectral imaging frames. Preliminary data streams are summarized in **Figure S1**. USBL data were first cleaned using robust outlier detection based on step-change thresholds and statistical filters. Identified outliers were replaced via linear interpolation to preserve continuity. After outlier removal, navigation data were smoothed using constant-velocity Kalman filters to reduce high-frequency noise while maintaining realistic platform motion. Altitude was treated as a one-dimensional state, while horizontal position was filtered jointly in two dimensions to preserve trajectory coherence. Filter parameters were tuned to minimize jitter without distorting overall movement. The resulting navigation tracks were stable, physically consistent, and suitable for downstream processing.

What enables timestamping of the acoustic positioning data is a custom-built signal control board (SCB), which ensures that each hyperspectral image line is synchronized in real time with GNSS/INS navigation data. Accurate timestamping is important for underwater geolocation, where navigation, positioning, and sensor acquisition must be aligned. Each hyperspectral image data acquisition start triggers the generation of a corresponding navigation file (*.nav*), which contains a combination of standard NMEA 0183 GPS sentences and proprietary Subsonos messages (see **Table S1** for message types included in these files). These records define frame capture events and accurately link them to GPS-referenced time, ensuring geospatial integrity of the pushbroom imagery.

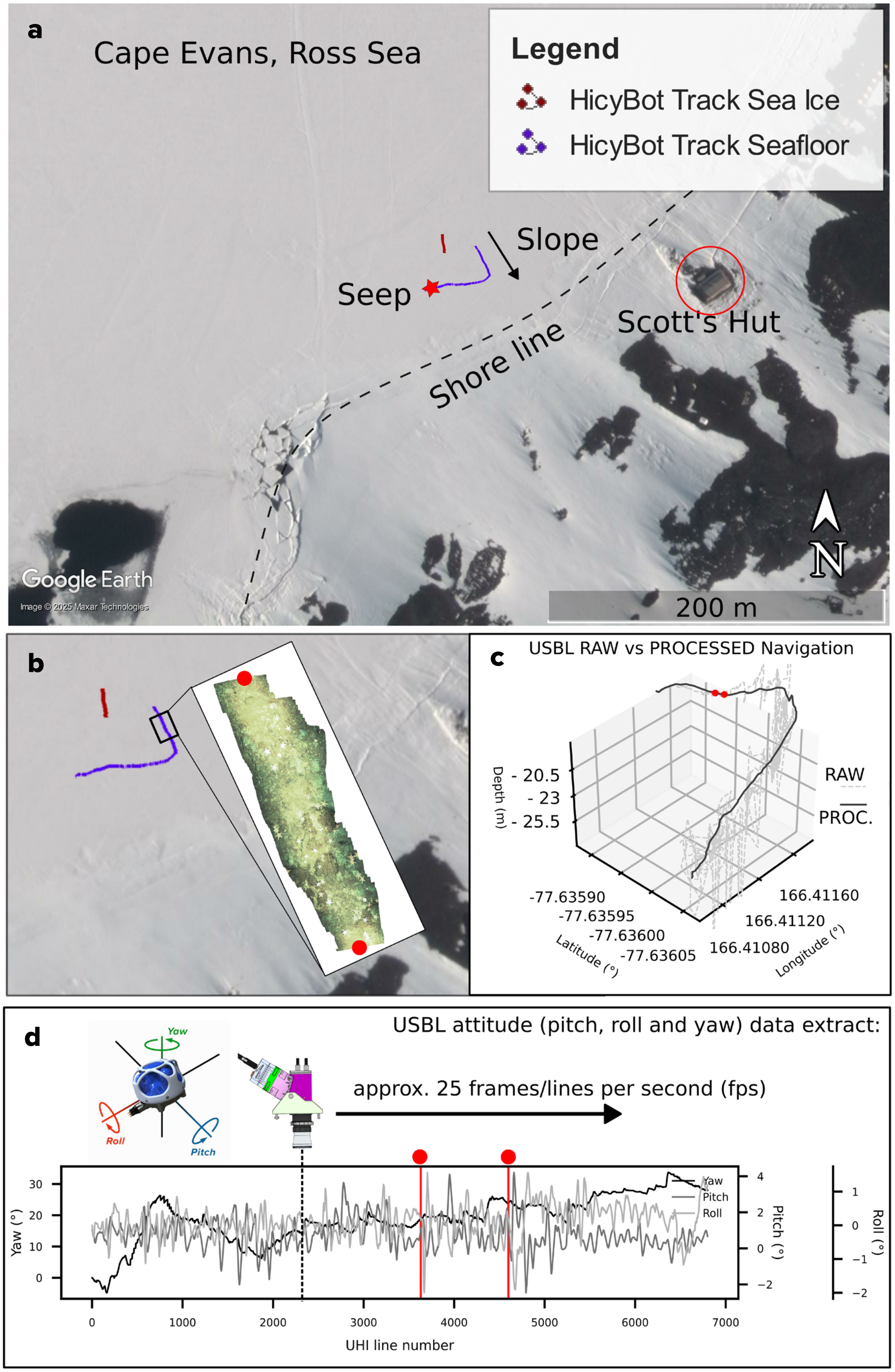

FIGURE S1. Example of navigation data extract used to synchronize underwater hyperspectral imaging (UHI) frames with ultra-short baseline (USBL) positioning. (a) Overview map showing the location of the sympagic (sea ice) and benthic (seafloor) transects featured in the main article, highlighting key coastal features such as the Antarctic methane seep and the shoreline slope. (b) Zoomed view of the two HIcyBot transects, with red markers indicating the start and end points of the extracted dataset referenced in Figure 3c. (c) Complete benthic transect imaging track as captured by HIcyBot, shown in both raw and processed forms within the WGS84 3D geodetic coordinate system. The trajectory follows the upward slope toward the coast and descends toward the seep site. (d) Extract of sensor attitude data (roll, pitch, yaw) used to align and georeference UHI pushbroom frame/lines. The arrow indicates direction of travel during scanning at 25 frames per second.

TABLE S1. Overview of message types used to timestamp and synchronize hyperspectral imaging frames with the Subsonus USBL acoustic positioning and attitude sensor. The messages follow the National Marine Electronics Association (NMEA) standard, which defines the format of GNSS-related data sentences commonly used across marine electronics for navigation and sensor integration.

MESSAGE TYPE	PURPOSE	KEY FIELDS	EXAMPLE AND NOTES
$SPTSMP	Survey frame capture marker (proprietary)	Frame counter, captured frames, flags	$SPTSMP,0,1,1*05 Indicates, for example, that frame capture has started with one frame recorded.
$GPZDA	UTC time and date	Time (hhmmss.ss), day, month, year	$GPZDA,230028.78,09,11,2023,00,00*68 Note: If it appears between unrelated sentences, frame-to-time alignment may be affected.
$GPGGA	GPS fix data (position, depth)	Time, latitude, longitude, fix quality, antenna altitude	$GPGGA,021623.34,7738.1508980,S,16624.6997948,E,6,00,9.9,-1.8,M,-54.0,M,,*78 Here, the latitude/longitude correspond to 77°38.1508980'S, 166°24.6997948'E; fix quality = 6; and antenna altitude = –1.8 m (1.8 m below surface). Note: positive = above sea level, negative = below sea level.
$PASHR	Attitude/heading (INS) (proprietary)	Heading, roll, pitch, heave, accuracies	$PASHR,230014.58,121.7,T,-04.45,+00.94,-00.01,00.186,00.186,00.349,0,1*31

IMAGE NORMALIZATION AND CONVERSION TO REFLECTANCE

Radiometric correction and conversion from raw digital numbers (DN) to spectral radiance was performed using Specim CaligeoPRO, which applies sensor-specific calibration and corrects for geometric and noise artifacts. For this study, spectral bands below 400 nm and above 700 nm were excluded due to high noise levels. Reflectance calibration was carried out using a secondary BlueROV2 equipped with an in-water Lambertian reference panel of known spectral properties. This support BlueROV2 was scanned at the same depth as each imaging transect, enabling correction for both natural and active (artificial) illumination conditions present during each deployment (Figure S2).

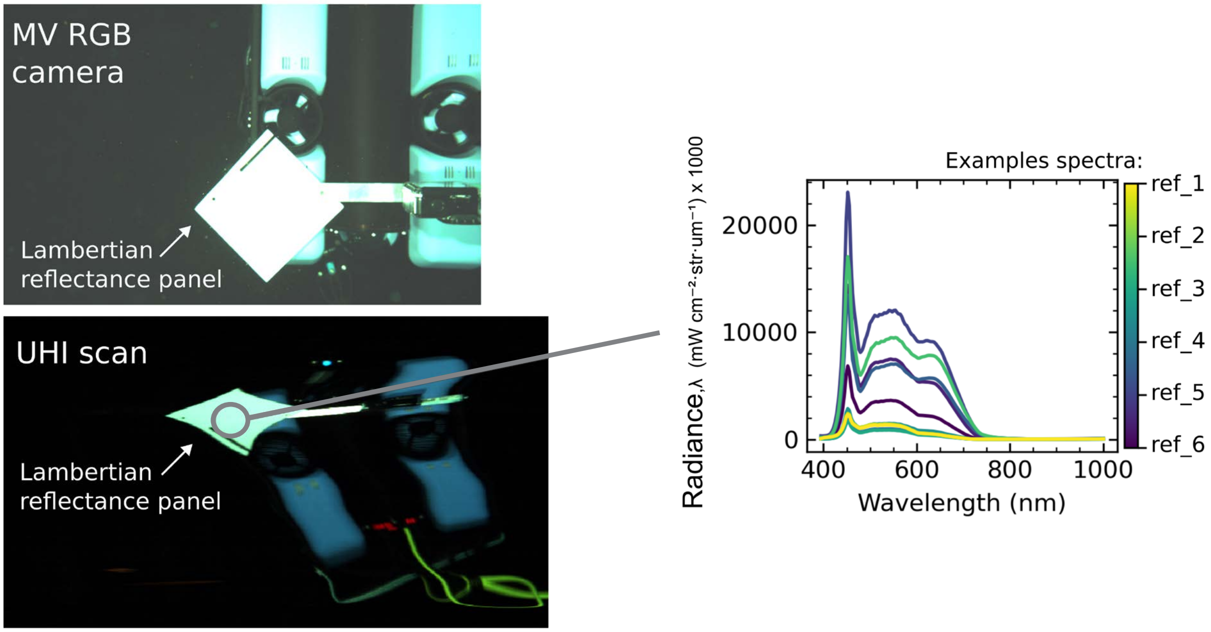

FIGURE S2. Example of reference light data used to convert the radiance calibrated hyperspectral imagery to reflectance. A Lambertian reflectance panel was attached to a support BlueROV2 which was navigated beneath HIcyBot to position the panel for imaging. The underwater hyperspectral imaging (UHI) camera, operating in a near-nadir orientation, scanned the panel at various distances and survey depths. The resulting spectra capture both natural ambient light and artificial illumination from KELDAN 8M (8000 lumens, CRI96) LEDs, providing calibration data that accounts for mixed lighting conditions encountered during surveys. MV RGB refers to the red, green and blue channels of the machine vision cameras.

SYSTEM TECHNICAL SPECIFICATIONS

A summary of the major system components, their manufacturers, software, and power requirements is provided in Table S2. The overall payload system architecture (Figure S3) illustrates the internal schematic of HIcyBot, detailing key components, data streams, and connectors that allow to synchronize all data, enabling concurrent data acquisition, real-time visualization stream, and logging across the imaging and navigation suite. As part of the system integration, sensor alignment offsets were carefully measured to support accurate georeferencing and future georectification workflows. Specifically, the spatial displacement between the hyperspectral camera's pupil entrance and the USBL acoustic positioning reference point was quantified in the X (platform-forward), Y (lateral), and Z (vertical) directions for both sea ice and seafloor configurations (Figure S4). These offsets are essential for calculating the true position and orientation of each frame, allowing for precise distance measurements to targets and accurate scaling of objects in the scene.

TABLE S2. Summary of all devices and sensors included in the HIcyBot payload, their specifications, software employed to operate them, and power consumption. fps = frames per second. ms = milliseconds. USB = ultra-short baseline. INS = inertial navigation system. GNSS = Global Navigation Satellite System. PTP = precision time protocol. PPS = pulse per second. IRIG = inter-range instrumentation group. NMEA = National Marine Electronics Association. SCB = signal control board. PoE = Power over Ethernet. DOF = degrees of freedom. CRI = color rendering index. VDC = volts direct current. Wh = watt-hours. lm = lumens.

DEVICE(S)	SPECIFICATIONS	SOFTWARE AND MANUFACTURER	VOLTAGE (VDC)	MAX POWER
• PC • Signal Control Board (SCB) • Frame Grabber (EPIX)	• OS: Windows • EPIX frame grabber: Camera Link/PCIe interface	**Custom via Specim Lumo SDK** Adept Turnkey Ltd., Melbourne, Australia	19 V	31 W
• Subsonos USBL	• (Advertised) Pos. accuracy: 0.1 m • Heading: 0.3° • Roll/pitch: 0.1° • Range/depth: 1,000 m • Freq: 30 kHz • 8-channel hydrophone array • Update rate: 10 Hz • Integrated INS + GNSS	**Web UI via Ethernet** Advanced Navigation, NSW, Australia	9–60 V (PoE)	~25 W avg
• Aisa Kestrel 10 — (AK10) Pushbroom hyperspectral camera	• Spectral range: 400–1,000 nm • Spatial pixels: 2,048 • Spectral bands: 380+ • Spectral sampling: 1.75/3.5/7 nm through binning spatial ×2, ×4, ×8 and spectral ×2, ×4, ×8 (combinable) • FOV: 40° Typical settings for HIcyBot surveys: • Sea-ice mode: 25 fps, 39 ms integration time, binning 4×2 • Seafloor mode: 15 fps, 65.7 ms integration time, binning 4×2	**Lumo Recorder and SDK** Specim Ltd., Oulu, Finland	12 V	45 W
• Low-Light USB camera	• Interface: USB (bus-powered)	**iSPY open source** Arducam, Nanjing, Jiangsu, China	5 V (PC USB)	≤5 W
• MV Genie Nano • Ricoh 12mm lens (×2) • GigE machine vision camera	• Sensor: Sony IMX249 (Pregius), 2/3" • Res: 1,920 × 1,200 (2.3 MP) • Pixel: 5.86 μm • FPS: 39.1 (TurboDrive) • Interface: GigE Vision PoE • Shutter: global electronic • Lens: 12mm C-Mount, 5MP	**eBUS SDK** Teledyne Dalsa Corp., Waterloo, Ontario, Canada, and Ricoh Company Ltd., Tokyo, Japan	10–36 V (12 V nom.) × 2	6.5 W × 2
• PTP to PPS converter • DC048 for IRIG to NMEA converter	• Converts: PTP IEEE-1588 → 1PPS, IRIG-B → NMEA-0183 • I/O: RS-422 / RS-232 / BNC • Timing accuracy: <20 ns (typical)	**N/A** Valiant Communications Ltd., USA	19 V	25.2 W
• BlueROV2 Heavy configuration kit	• Thrusters: 8 × T200 • Depth: 100 m (acrylic) / 300 m (aluminum) • Battery runtime: ~2 hrs moderate use • 6-DOF • Ethernet tether	**BlueOS, ArduSub, and QGroundControl** Blue Robotics Inc., CA, USA	14.8 V (LiPo)	10 Ah (148 Wh)
• Video lights 8M 8000 lm CRI96 LED	• Output: 2,700–8,000 lm (5 settings) • LED power: 28–105 W • Color temp: 5,600 K • CRI: 96; Beam: 90° • Depth rating: 200 m • Burn time: 45–170 min	**N/A** KELDAN GmbH, Brügg, Switzerland	14.4 V (Li-Ion)	28-105 W

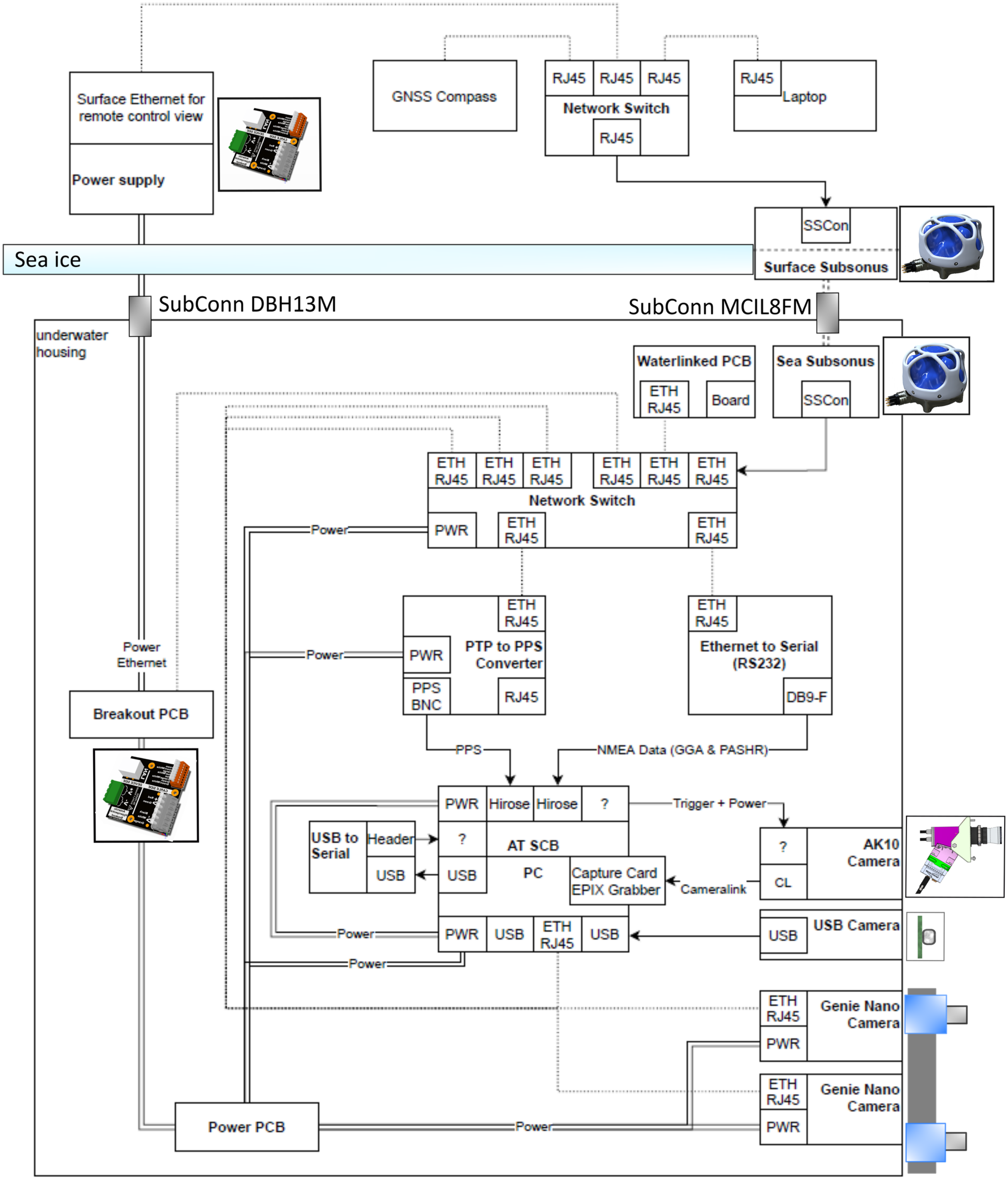

FIGURE S3. Internal schematic overview of the HIcyBot system, showing data streams, key components, and connectors. SubConn underwater connectors are used for power and communication: a 13-pin model supports Ethernet and main power lines, while an 8-pin model connects to the Subsonus USBL unit. PWR = power. PCB = printed circuit board. PPS = pulse per second timing signal. RJ45 = Ethernet (ETH) connector. AT SCB = adept turnkey signal control board. PTP to PPS refers to conversion from high-precision network timing (Precision Time Protocol, IEEE 1588) into a hardware pulse signal for synchronization.

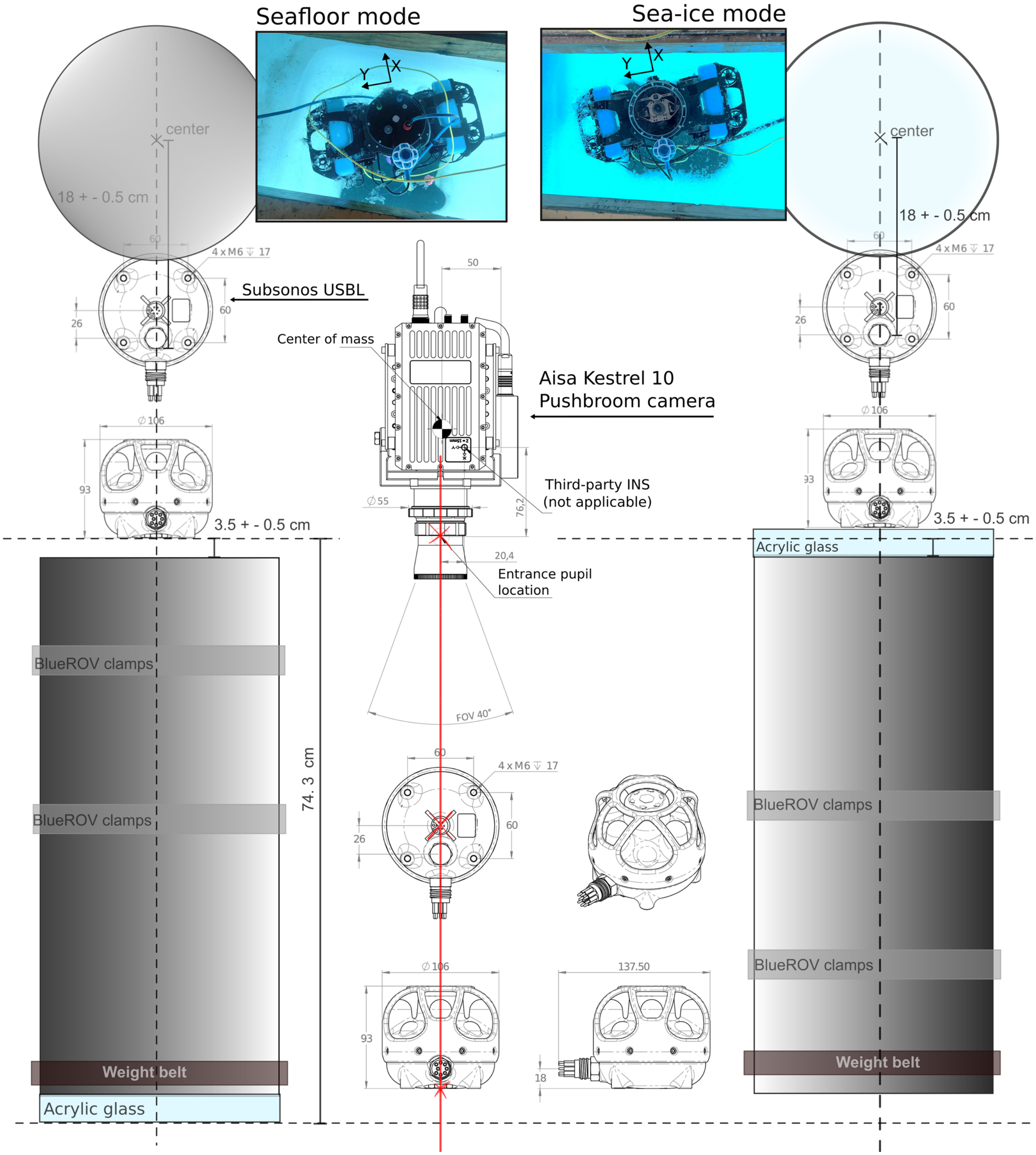

FIGURE S4. Sensor alignment offsets that are essential for georeferencing and georectification workflows. The misalignment between the hyperspectral camera's pupil entrance and the USBL acoustic positioning reference point was calculated in millimeters along the ROV coordinate axes, where **X** denotes the direction of forward movement, **Y** indicates lateral offset (sideways), and **Z** represents the vertical height of the system. In sea-ice mode, the offset was X = 134.50 mm, Y = 0 mm, Z = 118.83 mm; while in seafloor mode, the offset was X = 170.00 mm, Y = 0 mm, Z = 631.77 mm. The bottom weight belt maintains a nadir-oriented "pendulum" effect that improves imaging stability.