Ginan - Case Study

Australian Institute of Marine Science

Produced for Positioning Australia

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Acronyms and Abbreviations

Term	Definition
4G LTE	Fourth Generation Long-Term Evolution
AHD	Australian Height Datum
AIMS	Australian Institute of Marine Science
AMS	Autonomous Maritime Systems
ASV	Autonomous Surface Vessel
AUV	Autonomous Underwater Vehicle
AVG	Average
BCEP	Broadcast Ephemeris
BKG	German Federal Agency for Cartography and Geodesy
CDDIS	Crustal Dynamics Data Information System
CL	Confidence Level
CNR	Carrier-to-Noise Ratio
CORS	Continuously Operating Reference System
DRMS	Distance Root Mean Square
EDA	Exploratory Data Analysis
ENU	Easting, Northing, Up
Exif	Exchangeable Image File Format
GA	Geoscience Australia
GCP	Ground Control Points
GDA2020	Geocentric Datum of Australia 2020
GNSS	Global Navigation Satellite System
HAT	Hardware Attached on Top
IGS	International GNSS Service
ISR	Intelligence, Surveillance and Reconnaissance
ITRF2020	International Terrestrial Reference Frame 2020
LiPo	Lithium Polymer
NASA	U.S. National Aeronautics and Space Administration
NMEA	National Marine Electronics Association 0183
NPIC	National Positioning Infrastructure Capability
NTRIP	Networked Transport of RTCM via Internet Protocol
OS	Operating System
OSR	Observation Space Representation
PEA	Parameter Estimation Algorithm
PPK	Post-Processed Kinematic
PPP	Precise Point Positioning
RINEX	Receiver Independent Exchange Format
RMS	Root Mean Square
RPAS	Remotely Piloted Aircraft System
RPi	Raspberry Pi
RTCM3	Radio Technical Commission for Maritime Services 3
RTK	Real-time Kinematic
SBF	Septentrio Binary Format
SeaSim	National Sea Simulator
SLA	Sealed Lead Acid
SLAM	Simultaneous Localisation and Mapping
SPP	Single Point Positioning
SSH	Secure Shell
SSR	State Space Representation
SD	Standard Deviation
TRL	Technology Readiness Level
UART	Universal Asynchronous Receiver/Transmitter
UPS	Uninterruptible Power Supply
USB	Universal Serial Bus

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1. Introduction

1.1. Background

FrontierSI has been engaged by Geoscience Australia (GA) to establish a series of case studies showcasing the benefits of Positioning Australia products and services through demonstrations of precise positioning capability. The Australian Institute of Marine Science (AIMS) was selected as the demonstration partner for this case study, contributing their extensive knowledge of current and future marine technologies and providing a suitably challenging environment for deployment of precise positioning solutions. This project investigates the available options for provision of precise global navigation satellite systems (GNSS) positioning at the AIMS Marine Operations Centre, and explores the suitability, benefits, and challenges of using Positioning Australia products including Ginan for this purpose.

1.2. Australian Institute of Marine Science

AIMS is home to ReefWorks – Australia's tropical marine technology test range near Townsville, Australia. The test range is a collaborative ecosystem which allows a layered approach that can scale to meet future technological industry and research requirements. The rapid evolution of uncrewed platforms, remote real-time communication technologies and machine assisted data analysis technologies has reached a point where they can be reliably transitioned into routine marine field observations at sea. However, implementing efficient test and evaluation regimes for these next generation technologies is challenging.

Complex marine activities are often undertaken by a network of multiple platforms. This underpins the need of an adaptative test range supporting the various levels of autonomy of each individual platform and taking advantage of sustainable in-situ supporting infrastructure. Future test range communication capabilities must feature state of the art of technologies to enable unique collaboration between platforms and stakeholders in the most challenging remote tropical environments. Multi-parameter sensors and accurate geo-positioning instrumentation on the range allow platforms to test their redundancy and smart capabilities. This unique environment in which to test deployments of uncrewed technology on the Great Barrier Reef has become a key enabler to foster collaboration and efficiency to better protect our oceans.

AIMS has established a technology test range for Autonomous Maritime Systems (AMS), where clients can prove the capabilities of uncrewed vehicles and marine instrumentation in a controlled environment. The ReefWorks test ranges cater to solutions across Technology Readiness Levels (TRLs) 3-8 through 4 test areas: the test tanks at the National Sea Simulator (SeaSim), AIMS Inshore test range, Davies Reef and Myrmidon Reef test ranges. To support the testing and calibration of positioning, navigation, and timing solutions at ReefWorks, AIMS seeks to explore options for precise positioning capabilities using open-source low-cost and commercial-off-the-shelf solutions.

As an initial investigation, AIMS and FrontierSI have investigated the development of a ReefWorks Precise Positioning System for the Inshore test range area nearby to the AIMS Marine Operations centre at the AIMS Cape Ferguson site, which also hosts a Geoscience Australia owned and operated GNSS Continuously Operating Reference Station (CORS), recently upgraded as part of the National Positioning Infrastructure Capability (NPIC), and cellular communications coverage. AIMS has suggested two suitable test platforms for this demonstration: an Autonomous Surface Vessel (ASV), and a large Remotely Piloted Aircraft System (RPAS). AIMS and FrontierSI have jointly developed the positioning solution using Positioning Australia products integrated directly with these test platforms to assess the performance in test deployments in a representative environment at Cape Ferguson.

1.3. Positioning Australia

Through the Positioning Australia program, GA provides accurate, reliable and real-time positioning data across Australia and its maritime zones, which includes the necessary satellite and ground infrastructure to track, verify, optimise and deliver precise positioning data and services. Positioning Australia is delivering positioning services with accuracies as little as 10 cm across Australia and its maritime zones, and enabling positioning services with accuracies better than 5 cm in areas of mobile phone coverage. These capabilities will facilitate a wide range of positioning applications for new industries (e.g. intelligent transport systems, location-based services, precision agriculture) and enable existing industries to improve productivity, efficiency, safety and knowledge.

FrontierSI is collaborating with GA to address key underlying research and innovation questions to ensure that positioning data and services in Australia are accessible and adequately serve the needs of the new (non-specialist) users, who will emerge because of the rapid growth in the use of precise positioning applications.

1.4. Ginan

The Australian Government, through GA's Positioning Australia program, is funding the design, development and operational service of an open-source GNSS position correction system - the Ginan service and toolkit. This system will give individuals and organisations no-cost access to software and products that have the potential to greatly enhance the accuracy of positioning – to within a few centimetres across Australia. Ginan provides a suite of open-source tools that provide the capability to analyse GNSS data in real-time and generate products that support precise positioning solutions. Ginan is developed and maintained by GA in collaboration with industry and academic partners. Further information about Ginan is available on GA's Ginan webpage (Geoscience Australia, 2023), and technical information is available at Ginan's documentation webpage (Geoscience Australia, 2022).

1.5. FrontierSI

In support of the Positioning Australia program, FrontierSI has developed a "Ginan test-kit" to enable demonstration scenarios to be carried out with assistance of suitable industry and government partners. In a series of Ginan Case studies taking place in 2023, FrontierSI is providing specialist assistance in the design and integration of a variety of research platforms with Ginan's precise positioning capabilities. The knowledge and documentation produced through these integration and testing processes will form the basis of several case-studies to inform and support the development of Ginan as an open-source platform for research and innovation.

2. Methodology

2.1. Research Platforms

2.1.1. Surfbee Queen

Shown in Figure 1, the Surfbee Queen is a remotely piloted ASV used for testing at the AIMS Inshore test range developed by FireTail Robotics. The Surfbee has an inflatable hull that weighs 16kg, and it has the inflated dimensions of 2.2m x 0.8m x 0.15m. Its large size allows the deployment of heavier payloads of up to 30kg and has a range of integrated positioning and navigation features including an onboard GNSS positioning antenna and receiver, camera, waypoint navigation and position hold function.

The platform is ideal to support scientific research and speed up the testing on the range to undertake bathymetry mapping, surveillance activities or payload testing, in substantial safety with a high level of accuracy. ASVs like the Surfbee offer a flexible, moving platform for integration with additional hardware and software to enable a plethora of capabilities to be developed in alignment with ReefWorks future goals and requirements. When integrated with additional components, specialised ASV integrations can be developed for on-range activities, including but not limited to:

- Training operators in remotely piloted systems
- Conducting bathymetric mapping
- Developing accurate geo-fences around the test range for compliance purposes
- Detecting targets of interest or threat (e.g., crocodiles, simulated mines, or crown-of-Thorns starfish)
- Resilience testing against vehicle hacking and cybersecurity threats
- Tracking of underwater vehicles (by direct observation or triangulation)
- Detection of "lost" assets such as Autonomous underwater vehicles (AUVs)
- Asset inspection and security (e.g., pipes or cables)
- 4G & Wi-Fi connectivity mapping of areas
- Demonstration and testing of new payloads for deployment

In the demonstrations, Ginan is used to precisely position the Surfbee, independent to onboard positioning instrumentation. Due to the Surfbee's low profile, one of the key integration requirements is protecting the onboard hardware from water ingress. A water-resistant enclosure houses the equipment, which in turn requires internal hardware to use externally routed antennas. Additionally, close attention to heat management of the equipment is required.

Figure 1 The Surfbee Queen with Ginan onboard.

2.1.2. DJI Matrice 600

The DJI Matrice 600 Pro (M600) shown in Figure 2 is a fully autonomous RPAS also used to support scientific research at AIMS, it is used to support operations on the test ranges. The M600 weighs 9.5kg and has the unfolded dimensions of 1.6m x 1.5m x 0.7m. It has a maximum payload of 5.5kg and includes an onboard camera system for image and video capture.

The M600 and similar RPAS offer a significant payload capability, allowing flexibility in integration and enabling aerial oversight to a wide area of operation. The M600 as an aerial platform has the potential to enable capabilities to be developed in alignment with ReefWorks development goals. The M600 carries an onboard GNSS receiver, but offers only standalone positioning without augmentation, offering limited spatial resolution. When combined with additional components, specialised RPAS integrations could be developed for on-range activities, including but not limited to:

- Tracking of surface vehicles (including after mission reporting)
- Detection of vehicle proximity and collision avoidance
- Assessment of operational impact on marine life behaviour
- Developing accurate geofences around the test range for compliance purposes
- Mapping of obstructions for navigation safety
- Detecting targets of interest or threat (e.g., crocodiles, other vehicles)
- Tracking of underwater vehicles (by direct observation)
- Detection of "lost" assets such as AUVs

In the demonstrations, Ginan is used to precisely position the M600, independent to onboard positioning instrumentation. Since the M600 has a significantly smaller maximum payload, the integrated hardware needs to have a compact form factor and a light weight. However, the M600 is not restricted to the same water ingress protection requirements as the Surfbee.

Figure 2 The DJI M600 in flight with Ginan onboard.

2.2. Instrumentation

2.2.1. Hardware

The embedded Ginan system consists of four main hardware subsystems with auxiliary components.

1. Single Board Computer
2. GNSS Receiver
3. Uninterruptible Power Supply (UPS)
4. Modem

All four subsystems were used consistently across the Surfbee and M600 platforms, however the equipment differed slightly between integrations. Hardware components are presented in Table 1.

Table 1 Components of the embedded Ginan system.

Subsystem	Component	Function	Platform	
			Surfbee	M600
Single Board Computer	Raspberry Pi (RPi) 4 Model B, 8GB RAM	Execute Ginan, MQTT client, RTKLIB docker containers	✓	✓
	Heatsink kit	RPi cooling	✓	✓
	Sandisk 256GB micro SD Card	RPi disk storage	✓	✓
GNSS Receiver	Septentrio MosaicHAT, Mosaic-X5 variant	Process GNSS observations and positioning solutions	✓	✓
	Tallysman TW7972 w/ Ground Plane Triple Band GNSS patch antenna	Receive GNSS signals	✓	
	Tallysman HC977 Triple Band GNSS helical antenna	Receive GNSS signals		✓
	SMA coaxial cable	Connect GNSS antenna to MosaicHAT	✓	✓
	SMA Female to Female adapter	Connect GNSS antenna to MosaicHAT		✓
	SMA Male to Female right angle adapter	Connect GNSS antenna to MosaicHAT	✓	
	Micro USB to USB A cable	Enable additional USB serial ports of MosaicHAT	✓	✓
Uninterruptible Power Supply (UPS)	PiJuice Hardware Attached on Top (HAT)	Provide back-up power supply	✓	✓
	DiaMec 12V 7.2Ah Sealed Lead Acid (SLA) battery	Primary power supply	✓	
	USB Buck Converter	Steps down ~12V to 5V 3A	✓	
	Anker 13000mAh lithium polymer (LiPo) power bank	Primary power supply		✓
	Micro USB to USB A cable	Provides power from power supply to UPS	✓	✓
Modem	Teltonika RUT240 4G/LTE Cellular Modem	Provides internet connection	✓	
	Teltonika power cable w/ 4-way screw terminal	Provides power from power supply to Teltonika RUT240	✓	
	Zyxel NR2101 5G Modem	Provides internet connection		✓
	Blackhawk 4G Antenna	Antenna for Teltonika RUT240	✓	
	Ethernet cable	Interfaces RPi with modem	✓	✓
Auxiliary Components	3D Printed Enclosure	Protective enclosure for RPi	✓	✓
	Noctua 5V 40mm Fan	RPi cooling	✓	
	Pelican 1400 case	Water resistant enclosure for Surfbee equipment	✓	

Single Board Computer

The Raspberry Pi (RPi) 4B is the central single board computer responsible for the execution of Ginan and the supplementary Docker containers and also controls the data flow from the GNSS receiver. The RPi's light weight, small form factor and availability of compatible GNSS receiver hardware attached on top (HAT) modules makes it an ideal platform for integrating Ginan with AIMS' research platforms. A custom enclosure was designed, and 3D printed to house the RPi and connected HATs. It includes cut-outs to access buttons and input/output ports. It also has pilot holes aligned with the RPi's mounting holes, so that the case can be fixed directly onto standoffs.

GNSS Receiver

An Ardusimple MosaicHAT (Septentrio Mosiac-X5 GNSS module) GNSS receiver is connected to the RPi via the Universal Asynchronous Receiver/Transmitter (UART). Running firmware 4.12.1, the MosaicHAT is configured to provide a serial port over the UART, and two serial ports via USB (universal serial bus) cable. Each serial port allows bi-directional data flow between the RPi and the receiver. The UART serial port is configured for streaming Radio Technical Commission for Maritime Services 3 (RTCM3) GNSS observations which are processed by Ginan. The USB serial ports are used for logging Septentrio Binary Format (SBF) and National Marine Electronics Association 0183 (NMEA) data streams. See Appendix B – MosaicHAT Configuration Files for the configuration files used for testing. A GNSS antenna is connected via SMA coaxial cable to the MosaicHAT to receive GNSS signals. The Tallysman TW7972 patch antenna and the Tallysman HC977 helical antenna are used for the demonstrations, their integration is discussed further in Section 2.2.2.

Uninterruptible Power Supply

Also connected to the RPi via UART is a PiJuice uninterruptible power supply (UPS) HAT. The PiJuice HAT provides a 5V regulated power supply to the RPi and provides a backup power supply when the primary power supplies are discharged or require replacement during testing. The primary power supplies are connected to the PiJuice HAT with a USB-A to Micro-USB cable. The DiaMec 12V 7.2Ah Sealed Lead Acid (SLA) battery and the Anker 13000mAh lithium polymer (LiPo) are used as primary power supplies, this is discussed in Section 2.2.2.

Modem

A portable cellular modem provides an internet connection over the Telstra 4G network and allows secure shell (SSH) access to the RPi during the convergence periods. The RPi relies on an internet connection to request GNSS correction data from GA's Networked Transport of RTCM via Internet Protocol (NTRIP) caster and to also interface the MQTT client with the ReefWorks real-time operations Dashboard. The Teltonika RUT240 4G/LTE modem and the Zyxel NR2101 5G modem are used for the demonstrations, they are discussed further in Section 2.2.2.

2.2.2. Research Platform Integration

Surfbee

The Surfbee's hardware integration is illustrated in Figure 3.

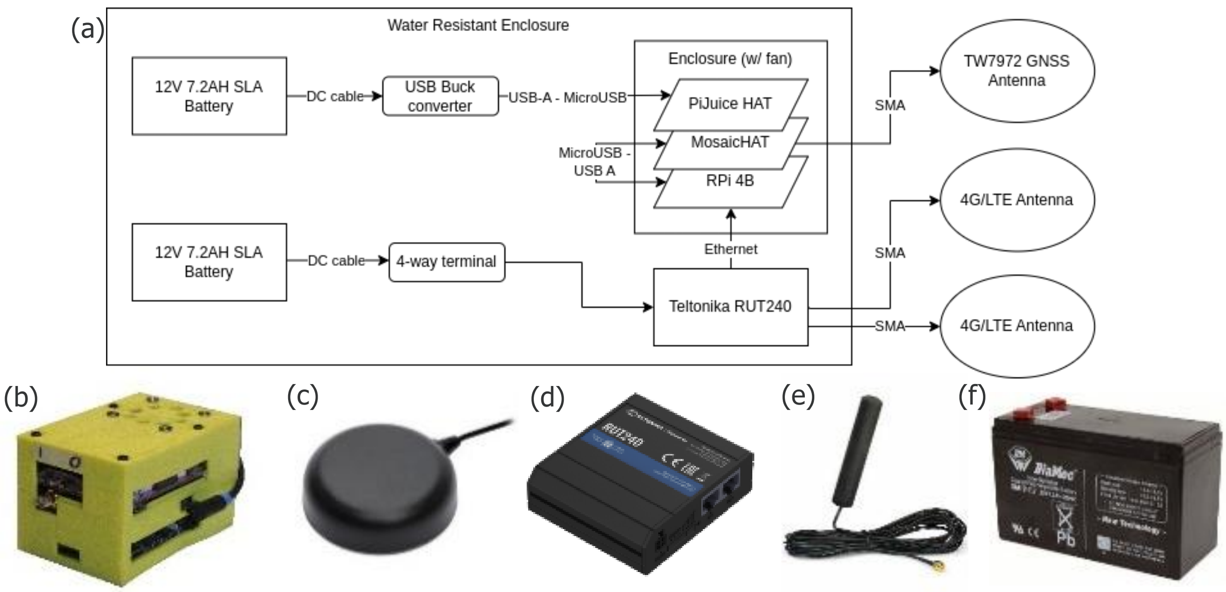

Figure 3 (a) Surfbee hardware integration diagram (b) Raspberry Pi, MosaicHAT and PiJuice HAT in enclosure (c) Tallysman TW7972 GNSS antenna (d) Teltonika RUT240 4G/LTE modem (e) Blackhawk 4G antenna (f) DiaMec 12V 7.2Ah SLA.

Shown in Figure 4, a Pelican case houses the hardware and provides protection from water ingress. Due to this, the enclosure for the RPi, MosaicHAT and PiJuice was modified to include a Noctua 5V 40mm fan to provide additional airflow. Furthermore, a DiaMec 12V 7.2Ah SLA battery is used as the RPi's primary power supply, a DC buck converter steps down ~12V to 5V 3A. The use of SLA batteries minimised the production of heat from the power supply. A Tallysman TW7972 triple band GNSS patch antenna with a ground plane is mounted on top of the Surfbee's camera system (see Figure 4) and is connected to the MosaicHAT with an SMA coaxial cable. The cable is routed through a cut-out of the Pelican case, with a water-resistant cable gland ensuring the water ingress properties are preserved. A Teltonika RUT240 4G/LTE cellular modem is mounted inside the Pelican case and two LTE antennas are mounted on the case's exterior with adhesive strips. As with the GNSS antenna's coaxial cable, the LTE antennas cables are routed through three cut-outs of the Pelican case through water resistant cable glands. An ethernet cable connects the modem to the RPi and an optional Wi-Fi antenna is connected to the modem to allow SSH connections to the RPi during convergence. The modem is powered by a second 12V 7.2Ah SLA via the Teltonika 4-way screw terminal power cable.

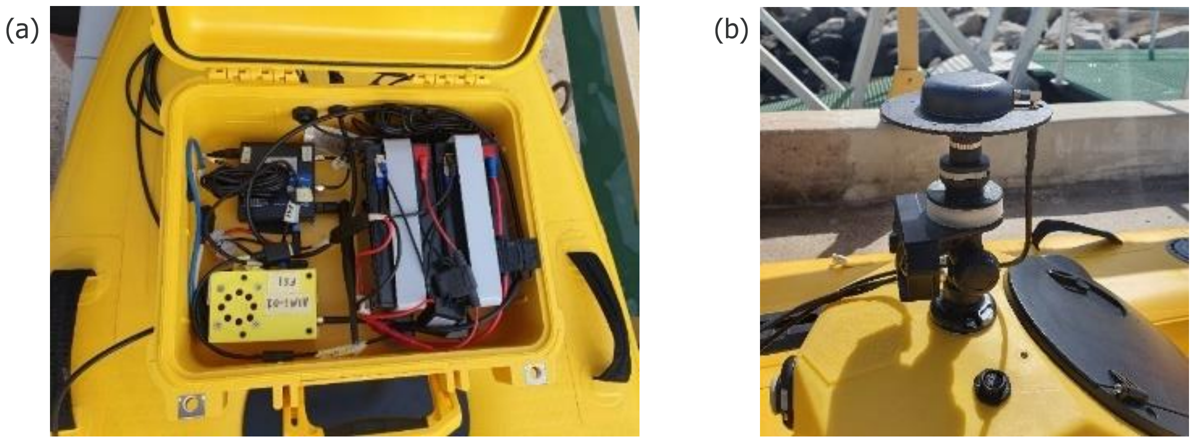

Figure 4 (a) Hardware inside the Pelican case (b) Tallysman TW7972 antenna mounting.

DJI M600

The DJI M600's hardware integration is illustrated in Figure 5.

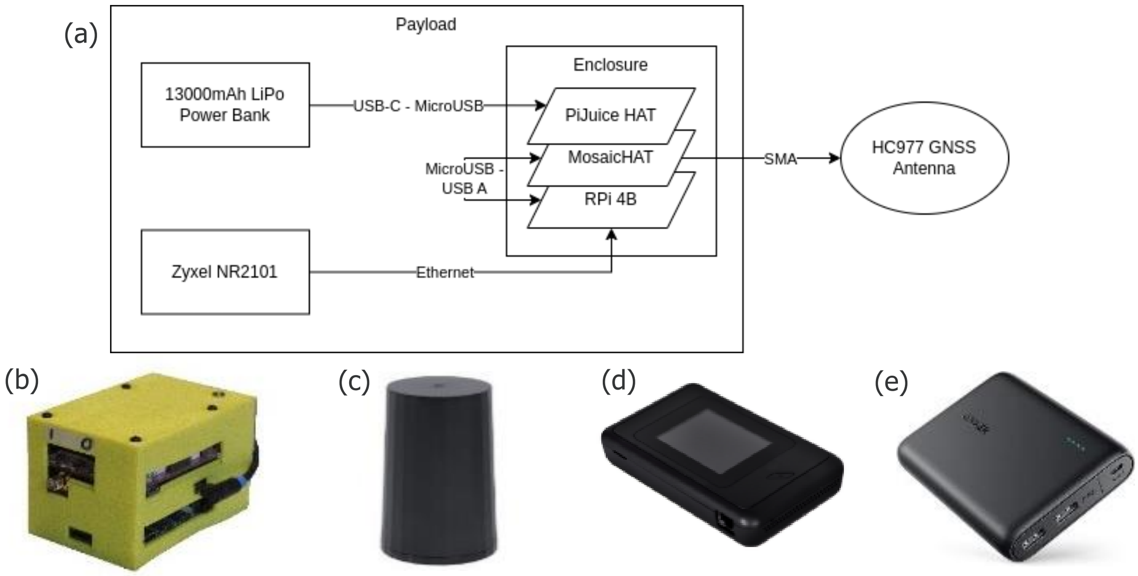

Figure 5 (a) DJI M600 hardware integration diagram (b) Raspberry Pi, MosaicHAT and PiJuice HAT in enclosure (c) Tallysman HC977 GNSS antenna (d) Zyxel NR2101 modem (e) Anker 13000mAh LiPo power bank.

The M600 integration calls for equipment that is lightweight and has a small form factor, as it is all mounted from a plastic bracket cable tied to the M600's payload mounting rails. The power supply is an Anker 13000mAh LiPo power bank. The M600 integration does not have the same water ingress requirements as the Surfbee, allowing equipment to be passively cooled when the M600 is in flight. A Tallysman HC977 triple band GNSS helical antenna is used for the M600, one of the major advantages of helical antennas is their light weight. The antenna is mounted on a steel bracket attached to the M600's central frame and connected to the MosaicHAT with an SMA coaxial cable. A Zyxel NR2101 5G modem provides an internet connection for RPi via an ethernet cable. It is compact, lightweight and has an internal antenna and power supply which simplifies mounting options. It is cable tied onto the upper plate of the camera system.

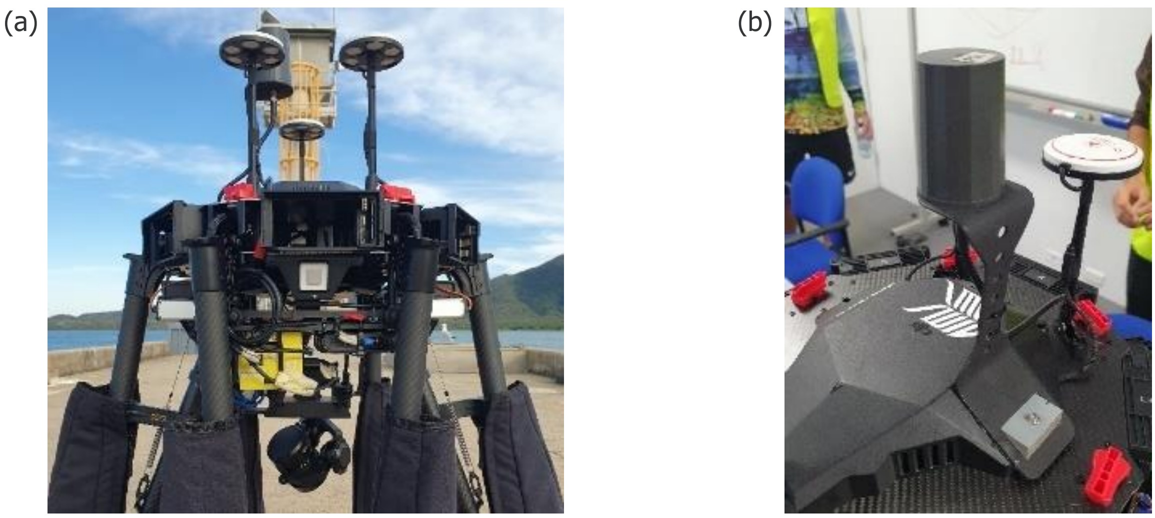

Figure 6 (a) Hardware mounted to the payload rails (b) Tallysman HC977 antenna mounting.

2.2.3. Software

The operating system (OS) hosted on the RPi is Raspberry Pi OS Lite 64-bit (Debian 11 Bullseye). A software package has been developed with Docker to build and deploy multiple applications within a defined environment. The package consists of four main containers:

1. Ginan
2. MongoDB
3. MQTT Client
4. RTKLIB

The containers (or services) are orchestrated using the Docker Compose tool defined in by the docker-compose.yaml configuration file, and run-time variables are defined in the .env file. Each service's restart policy is set to 'unless-stopped' which allowed the package to restart upon boot. Docker build instructions are defined in a Dockerfile for each service.

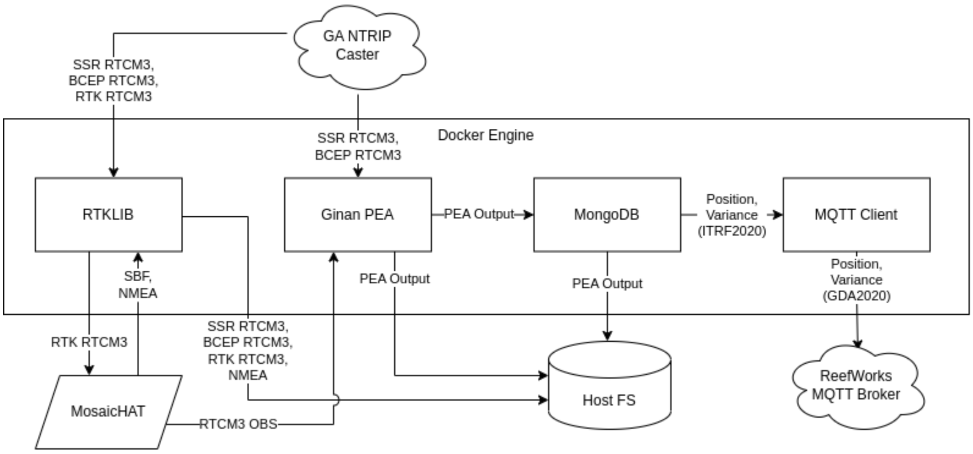

Figure 7 Docker service architecture & data flow.

Ginan

Access to the Ginan source code repository was provided to the project development team, and a Docker image of pre-release version 2.0 (commit 46f5c10, develop branch) was built for ARM64 architecture using the Docker buildx tool. The Dockerfile of the base image was modified to reduce the number of dependencies. Python 3 was removed since it is only used for the Exploratory Data Analysis (EDA) tool, and doxygen, graphviz and latex were removed as they are only used for building documentation. Additionally, MongoDB was removed and implemented as a separate Docker container. These modifications sped up the image building process and reduced the resulting image size. The MosaicHAT's serial port streaming RTCM3 data is forwarded as a device to the container and a local data volume is mounted in the container to allow persistent data logging.

MongoDB

MongoDB is a document-oriented database that the Ginan Parameter Estimation Algorithm (PEA) writes output to in real-time. It is the database that interfaces the MQTT client with Ginan's receiver position estimations. The official MongoDB image (version 4.4.18 Focal) from Docker Hub is used. To initialise MongoDB, an additional container is instantiated that connects to the MongoDB and executes a command to deploy a replica set. This is required to allow monitoring of updates to the database via change streams. The service is started with a local volume mounted so that the Ginan database can be retrieved.

MQTT Client

A Python MQTT client has been developed to integrate Ginan's positioning stream with AIMS' ReefWorks real-time operations Dashboard developed based on an open-source automation platform. The client monitors updates to the MongoDB using a change stream, the receiver position cartesian coordinates and variances are queried. At each update the cartesian coordinates are transformed from the International Terrestrial Reference Frame 2020 (ITRF2020) to the Geocentric Datum of Australia 2020 (GDA2020) and the resulting cartesian coordinates are converted to geodetic coordinates. The GeodePy python package are used to perform coordinate transformation and conversions. The coordinates, alongside the receiver position component variances and the RPi's CPU temperature are parsed into an MQTT JSON payload and published to the Home Assistant MQTT broker. The Eclipse Paho MQTT python package is used for connecting and publishing to the MQTT broker integrated with the ReefWorks Dashboard.

RTKLIB

An RTKLIB service is deployed for streaming Observation Space Representation (OSR) RTK corrections to the MosaicHAT, logging of the MosaicHAT's serial ports and logging GA's NTRIP streams. SBF raw GNSS observations and NMEA data streams are logged from the MosaicHAT. The State Space Representation (SSR) corrections and broadcast ephemeris streams used by Ginan are also logged with RTKLIB for redundancy.

2.3. Positioning Methods

Three methods of GNSS positioning are employed for the demonstrations:

1. Real-time kinematic (RTK)
2. Ginan Precise Point Positioning (PPP)
3. Post-Processed Kinematic (PPK)

These are facilitated by the MosaicHAT's capability of outputting three separate data streams. Each method is discussed further below.

2.3.1. Real-time Kinematic (RTK)

RTK is a GNSS positioning technique based on determining position relative to simultaneous observations from one, or a network of base stations with accurately known positions. These simultaneous observations allow the calculation of double differences which eliminate receiver and satellite clock errors and significantly reduces ionospheric and tropospheric delay. It can typically achieve an instantaneous centimetre-level positioning accuracy in real-time, however accuracy is dependent on the distance from the base stations (baseline) since errors are spatially correlated, it requires an internet connection to connect to an NTRIP caster and the differencing technique also introduces signal noise.

The Cape Ferguson (TOW200AUS) CORS from GA is located at AIMS, approximately 800m from the inshore test range. RTCM3 OSR corrections are streamed from the Cape Ferguson CORS to the MosaicHAT, and the internal positioning engine is used to process a multi-GNSS RTK solution which is output in an NMEA format. Table 2 lists the NMEA messages output from the MosaicHAT.

Table 2 MosaicHAT NMEA message output.

NMEA Message	Description
GNGGA	Time, position, and fix related data.
GNGLL	Position data: position fix, time of position fix, and status.
GNGSA	GNSS DOP and active satellites.
GNGST	Position error statistics.
GNGSV	Number of SVs in view, PRN, elevation, azimuth, and SNR.
GNRMC	Position, Velocity, and Time.
GNVTG	Actual track made good and speed over ground.

2.3.2. Ginan Precise Point Positioning (PPP)

Precise Point Positioning (PPP) is a GNSS positioning technique that combines GNSS satellite observations with satellite orbit and clock corrections, and error models in a mathematical algorithm to estimate position. PPP is a more scalable positioning technique compared to RTK. While an internet connection is often required (although satellite-based PPP is possible), it does not depend on simultaneous observations from a separate base station. However, it is subject to a convergence period to allow the algorithm to improve its positioning estimate. Typically, sub-decimetre level accuracies can be obtained following a 30–60-minute convergence period.

The Ginan PEA is an implementation of PPP based on a Kalman filter algorithm, it is configured to process a multi-GNSS (GPS, GLONASS and Galileo) positioning solution from RTCM3 GNSS observations streamed from the MosaicHAT, see Table 3 for the list of RTCM3 messages. The PEA also requests RTCM3 SSR corrections and RTCM3 broadcast ephemeris from GA's NTRIP caster. The SSRA02IGS1 RTCM SSR stream is used in the demonstrations, it is a Kalman filter combination including orbit and clock corrections for GPS, GLONASS and Galileo satellites produced by the International GNSS Service's (IGS). As for broadcast ephemeris, the BCEP00BKG0 RTCM3 stream is used, it applies to GPS, GLONASS, Galileo, Beidou, QZSS and SBAS satellites and is produced by the German Federal Agency for Cartography and Geodesy (BKG). The PEA configuration is largely the same for the Surfbee and M600, they only difference is setting a larger process noise parameter for the rate of change of the station's position for the M600 as higher velocities and accelerations were expected for the M600. See Appendix C – Ginan Configuration Files.

Table 3 MosaicHAT RTCM3 message output.

RTCM3 Message	Description
1006	Stationary RTK Reference Station ARP & Antenna Height.
1013	System Parameters, time offsets, lists of messages sent.
1019	GPS Broadcast Ephemeris.
1020	GLONASS Broadcast Ephemeris.
1033	Receiver and Antenna Descriptors.
1042	BeiDou Broadcast Ephemeris.
1044	QZSS Broadcast Ephemeris.
1045	Galileo F/NAV Ephemeris.
1046	Galileo I/NAV Ephemeris.
1077	GPS MSM7 (Pseudorange, PhaseRange, Doppler, CNR, with high resolution).
1087	GLONASS MSM7 (Pseudorange, PhaseRange, Doppler, CNR, with high resolution).
1097	Galileo MSM7 (Pseudorange, PhaseRange, Doppler, CNR, with high resolution).
1117	QZSS MSM7 (Pseudorange, PhaseRange, Doppler, CNR, with high resolution).
1127	BeiDou MSM7 (Pseudorange, PhaseRange, Doppler, CNR, with high resolution).
1230	GLONASS L1 and L2 Code-Phase Biases.

2.3.3. Post-Processed Kinematic (PPK)

Post-processed kinematic (PPK) is a GNSS positioning process that uses software to determine position(s) from GNSS observations after the data has been collected. A wide range of GNSS post-processing software is available and they typically employ differencing or PPP techniques as described above. Post-processing techniques have the added benefit of taking advantage of the whole timeseries of data, which allows for additional processing methods such as combining forward and backward processing and smoothing. Additionally, the process allows the use of final satellite orbit and clock products which are more accurate than those broadcast from the satellite. The resulting positioning solutions are of a higher accuracy than that of real-time methods, as such, the PPK process is used to determine the "ground-truth" trajectories that form the basis for comparing the RTK and PPP methods.

For the demonstrations, the OnPoz EZSurv software package is used in differential positioning mode. The SBF files logged from the MosaicHAT are converted to Receiver Independent Exchange Format (RINEX) format using the Septentrio SBF Converter application. GNSS observations from Cape Ferguson (TOW200AUS) are retrieved from GA's GNSS Data Centre, and final orbits and clocks for GPS and GLONASS, produced by the IGS, are retrieved from the U.S. National Aeronautics and Space Administration (NASA) Crustal Dynamics Data Information System (CDDIS). The data is imported into EZSurv and is processed using GPS, GLONASS and Galileo constellations in dual-frequency mode.

2.4. Test Methods

Five tests were conducted over the course of four days of data collection activities at the inshore test range. Four independent data sessions were collected with the Surfbee and five were collected with the M600, additionally the M600 captured images and video of remote objects during some of the sessions. Each test is further described below.

2.4.1. Test 1 – Ginan Convergence

The first test concerns the Ginan PEA static PPP convergence periods at the beginning of each data collection session. A minimum of 60 minutes was allocated for convergence during each session. The test involved setting up the hardware, executing the software on the RPi and monitoring the positioning output on the ReefWorks Dashboard. For the Surfbee, this involved resting the Surfbee on a trestle table on the wharf in close proximity to the ramp leading down to the pontoon. The equipment was set up inside the Pelican case and turned on. The Pelican case was left open to allow airflow to passively cool the equipment. The M600 was set up further along the wharf and the hardware was turned on to begin the convergence process.

Typically, a PPP solution is considered converged once positioning errors reach a certain threshold and remain under the threshold for a defined time period. In this case study, a PPP solution is considered converged when the horizontal and vertical positioning errors are less than 20cm for 10 minutes. For each session, the output NMEA datasets are analysed in a Jupyter Notebook, where easting, northing and up (ENU) errors are computed with respect to the PPK ground truth for every epoch. The time taken to meet the convergence criteria is reported for each session in the results section.

(a) (b)

Figure 8 Images of the (a) Surfbee and (b) DJI M600 during static convergence.

2.4.2. Test 2 – Positioning Performance

The second test involves an analysis of the positioning performance of the RTK and PPP datasets for each session. Following a static convergence period of at least 60 minutes, the platforms are deployed for data collection activities that aim to fulfil Tests 3, 4 and 5. The Surfbee platform was prepared for deployment by clamping down the Pelican case to a mounting deck with a ratchet strap. It is carried down to the pontoon where the thrusters are attached and tested, and then it is launched into the water where it is remotely piloted to collect positioning data for the testing activities. The M600 is prepared for flight by folding out the propellor arms and inserting the batteries. Once the M600 is powered, its flight is controlled remotely, and is used to capture images and videos for the testing activities.

The RTK and PPP NMEA datasets for both the Surfbee and the M600 are analysed in a Jupyter Notebook where ENU errors are computed from the PPK trajectory. The time series are trimmed to exclude the static convergence and any additional set up time, then the resulting positioning errors are used to compute performance statistics for the horizontal and vertical components. The average (AVG), standard deviation (SD), and root mean square (RMS for the vertical component and distance root mean square [DRMS] for the horizontal component) are computed which, assuming errors follow a Gaussian distribution these statistics can be used to indicate the bias, precision, and accuracy respectively. The RMS corresponds to a confidence level (CL) of approximately 63.2% - 68.3% for horizontal accuracy and 68.3% for vertical accuracy.

2.4.3. Test 3 – Position Determination of Tracked Surface Target

The third test aims to use the M600's onboard camera system to determine the position of the Surfbee deployed within the inshore test range. This involved deploying the M600 and Surfbee simultaneously, and performing three different manoeuvres:

1. M600 capturing automated orthophoto of the Surfbee lingering in the inshore test range.
2. M600 capturing top-down video of the Surfbee moving in the inshore test range.
3. M600 capturing oblique video of the Surfbee moving in the inshore test range.

During the M600 flights, four ground control points (GCPs) were captured in the imagery and video. These GCPs were surveyed with RTK by occupying them with a Septentrio Mosaic-X5 and a Tallysman TW7972 for approximately 10 minutes each. Two of the GCPs are published survey marks, the horizontal coordinates are in agreement with those from the RTK survey, GCP1 has a horizontal error of 194m and GCP2 has a horizontal error of 183m, both GCPS fall within the published mark's horizontal uncertainties of 250m. Both vertical heights of the GCPs from the RTK survey are in agreement to within 0.01m of the published marks when AUSGeoid2020 is used to derive Australian Height Datum (AHD) heights from the RTK survey's ellipsoid heights.

Ultimately, these data collection activities were undertaken to support further research and development of real-time positioning capabilities, fusing GNSS and image-based positioning. For this case study, a comparison of the static horizontal position of the Surfbee determined by the directly georeferenced orthophoto processed with single point positioning (SPP), the Surfbee's position on an indirectly georeferenced orthophoto (using four GCPs), and the Surfbee's RTK and PPP position is performed by comparing these four measurements to the PPK ground truth. The indirect georeferencing process was undertaken in QGIS, where the orthomosaic is georeferenced to four GCPs around the perimeter of the inshore test range. A projective transformation was performed with nearest-neighbour resampling. The timestamp of the Surfbee's position in the orthomosaic is required to determine the comparable coordinates of the various positioning methods. It was derived from the exchangeable image file format (Exif) metadata of the raw images. Three frames include the Surfbee, so the timestamp of the image that has the Surfbee closest to the centre of the image was adopted. Finally, the Surfbee's antenna horizontal position in the orthomosaic is determined using a crude digitisation method in QGIS. Shown in Figure 9, the centreline of the Surfbee was approximated and the antenna was determined along the centreline by a measured offset from the rear of the Surfbee (0.610m).

The M600's video outputs will not be processed or analysed as part of this project scope, instead a discussion on developing various image-based positioning capabilities is provided in the Recommendations.

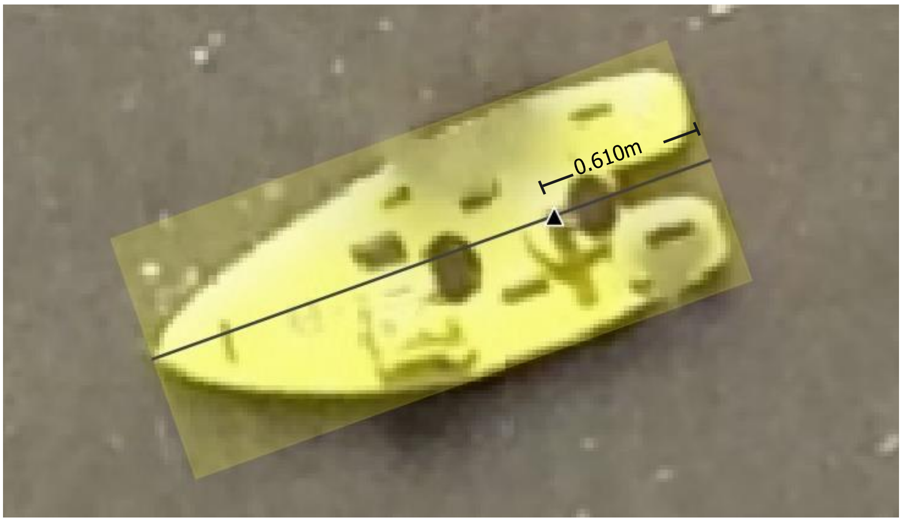

Figure 9 Determining the antenna position on the Surfbee.

2.4.4. Test 4 – Position Determination of Surveyed Underwater Target

The fourth test aims to use the M600's camera system to determine the position of an underwater PVC pipe within the inshore test range. This involved deploying a PVC pipe underwater within the test range, determining the horizontal position of the pipe using the Surfbee, then capturing imagery and video using the M600, including:

1. M600 capturing automated orthophoto of the pipe in the inshore test range.
2. M600 capturing top-down video of the pipe in the inshore test range.
3. M600 capturing oblique video of the pipe in the inshore test range.

As with Test 3, during the M600 flights the four GCPs were captured to allow for future processing. For this case study, a comparison of the horizontal position of the pipe as determined by the directly georeferenced orthophoto, the indirectly georeferenced orthophoto and pipe's surveyed position from RTK and PPP is performed by comparing these four measurements to the pipe's surveyed position from the Surfbee's PPK ground truth.

The pipe was deployed with a chain routed through it and anchors attached to each side to minimise movement. Buoys were also attached to the chain to provide reference points for the pipe's end points and to ensure the pipe could be retrieved. The horizontal position of the pipe was surveyed with the Surfbee. The survey was based on the assumption that the pipe was located at the centre of the two buoys, it involved briefly lingering the Surfbee between the buoys four times. Then to provide additional checks, the Surfbee was driven between the buoys from one to another two times, and then driven perpendicular to the orientation of the two buoys through the centre. From the resulting data, the four Surfbee clusters above the pipe were averaged to get a single horizontal coordinate, representing the centre point of the pipe for each positioning method.

The indirect georeferencing process followed the same process in Test 3, it was performed in QGIS using the four GCPs with a projective transformation and nearest-neighbour resampling. The pipe was then digitised in both orthomosaics by drawing a polyline down the centre of the pipe, then the centroid of the line was adopted as the reference point, see Figure 10.

As with Test 3, the M600's video outputs will not be processed or analysed as part of this project scope, instead a discussion on developing various image-based positioning capabilities is provided in Section 5

Figure 10 Determining the reference position on the pipe.

2.4.5. Test 5 – Position Determination of Untracked Wildlife

The fifth test aims to use the M600's camera system to determine the position of untracked marine wildlife. Using the M600, oblique video was captured of the GCPs, then video of various marine life in the inshore test range was captured. Using this video, the position of the marine life can be derived using photogrammetry and object detection techniques. However, the video processing to perform this analysis is out of the scope of this case study, so there are no results presented for this test. Instead, the data has been collected to facilitate further research and development, and a range of recommendations for the development of this capability are provided in Section 5.

3. Results

3.1. Test 1 – Ginan Convergence

3.1.1. Surfbee

Table 4 Ginan convergence times for the Surfbee.

Session	Convergence Time (minutes)	
	Horizontal	Vertical
1	-	33
2	15	16
3	30	50
4	29	21

- Session did not converge to less than 20cm for 10 consecutive minutes.

3.1.2. DJI M600

Table 5 Ginan convergence times for the DJI M600.

Session	Convergence Time (minutes)	
	Horizontal	Vertical
1	-	-
2	-	-
3	33	47
4	-	-
5[1]	50	26

1. Session 5 is post-processed with Ginan real-time simulation.

- Session did not converge to less than 20cm for 10 consecutive minutes.

3.2. Test 2 – Positioning Performance

3.2.1. Surfbee

Table 6 Positioning performance statistics for the Surfbee.

Session	Positioning Method	Horizontal (m)			Vertical (m)		
		AVG	SD	DRMS	AVG	SD	RMS
1	Ginan PPP	0.039	0.049	0.062	0.003	0.048	0.048
	Mosaic-X5 RTK	0.002	0.006	0.006	-0.006	0.009	0.011
2	Ginan PPP	0.048	0.022	0.052	0.116	0.044	0.124
	Mosaic-X5 RTK	0.002	0.005	0.005	-0.005	0.009	0.010
3	Ginan PPP	0.240	0.056	0.247	-0.083	0.050	0.097
	Mosaic-X5 RTK	0.001	0.005	0.005	-0.012	0.009	0.015
4	Ginan PPP	0.112	0.017	0.114	-0.012	0.040	0.042
	Mosaic-X5 RTK	0.002	0.004	0.004	-0.007	0.004	0.008

3.2.2. DJI M600

Table 7 Positioning performance statistics for the DJI M600.

Session	Positioning Method	Horizontal (m)			Vertical (m)		
		AVG	SD	DRMS	AVG	SD	RMS
1	Ginan PPP	0.156	0.019	0.157	-0.472	0.044	0.474
	Mosaic-X5 RTK	0.005	0.006	0.008	-0.002	0.013	0.013
2	Ginan PPP	0.152	0.036	0.156	-0.039	0.039	0.055
	Mosaic-X5 RTK	0.002	0.007	0.007	-0.002	0.014	0.014
3	Ginan PPP	0.131	0.026	0.133	-0.103	0.087	0.135
	Mosaic-X5 RTK	0.002	0.004	0.005	-0.006	0.007	0.009
4	Ginan PPP	0.490	0.058	0.493	-0.461	0.123	0.477
	Mosaic-X5 RTK	0.006	0.009	0.011	-0.003	0.013	0.014
5	Ginan PPP[1]	0.116	0.013	0.117	-0.006	0.023	0.024
	Mosaic-X5 RTK	0.002	0.005	0.005	-0.004	0.006	0.007

1. Session 5 is post-processed with Ginan real-time simulation.

3.3. Test 3 – Position Determination of Tracked Surface Target

Table 8 Horizontal error of the orthophoto ground control points.

GCP	Registered Mark No.	Name	GCP Horizontal Error (m)
1	112147	Granite Rock West Steel Bolt	2.391
2	112148	Granite Rock East Steel Bolt	2.806
3	N/A	Jetty Painted White Cross	2.736
4	N/A	Wharf Painted White Cross	2.512

Further information about the location of the GCPs is provided in Appendix D – Ground Control Points.

Table 9 The Surfbee's horizontal error for each positioning method.

Positioning Method	Horizontal Error (m)
Onboard Ginan PPP	0.062
Onboard Mosaic-X5 RTK	0.002
Indirectly Georeferenced Orthomosaic	0.030
Directly Georeferenced Orthomosaic	2.560

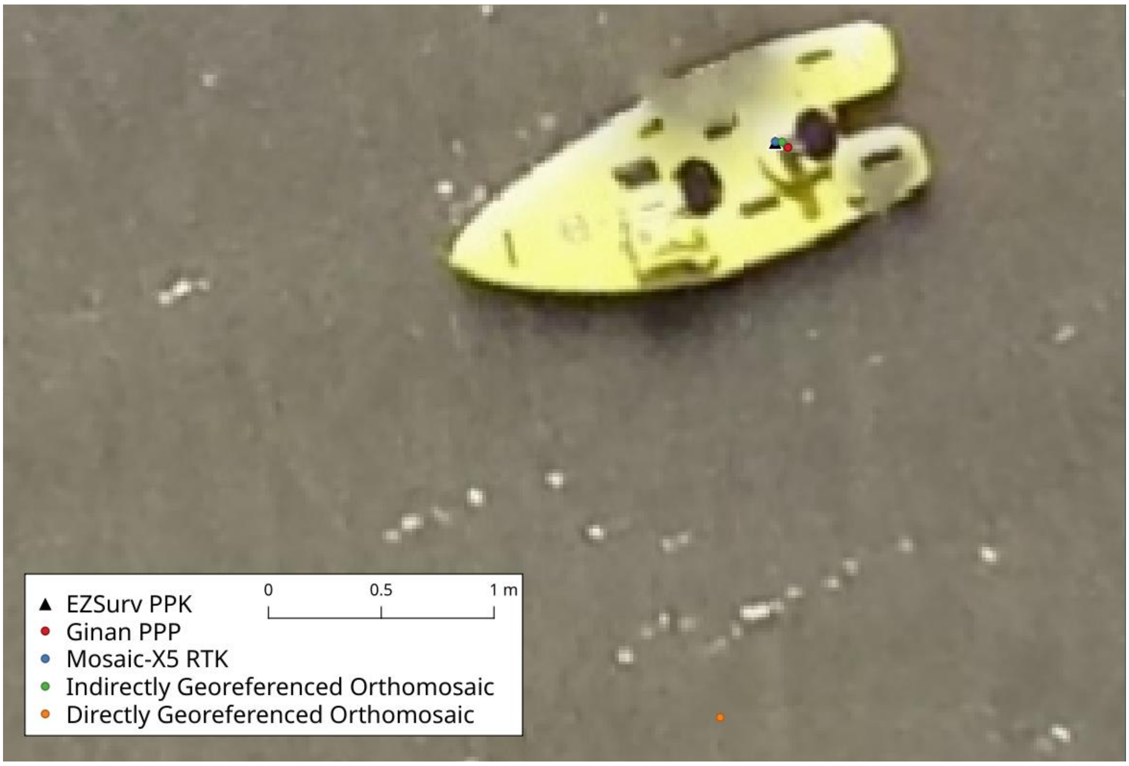

Figure 11 Map of the Test 3 Orthomosaic with each method's position overlayed.

3.4. Test 4 – Position Determination of Surveyed Underwater Target

Table 10 Horizontal error of the orthophoto ground control points.

GCP	Registered Mark No.	Name	GCP Horizontal Error (m)
1	112147	Granite Rock West Steel Bolt	4.283
2	112148	Granite Rock East Steel Bolt	3.504
3	N/A	Jetty Painted White Cross	3.829
4	N/A	Wharf Painted White Cross	4.022

Further information about the location of the GCPs is provided in Appendix D – Ground Control Points.

Table 11 The pipe's horizontal error for each positioning method.

Positioning Method	Horizontal Error (m)
Onboard Ginan PPP	0.194
Onboard Mosaic-X5 RTK	0.003
Indirectly Georeferenced Orthomosaic	1.209
Directly Georeferenced Orthomosaic	5.034

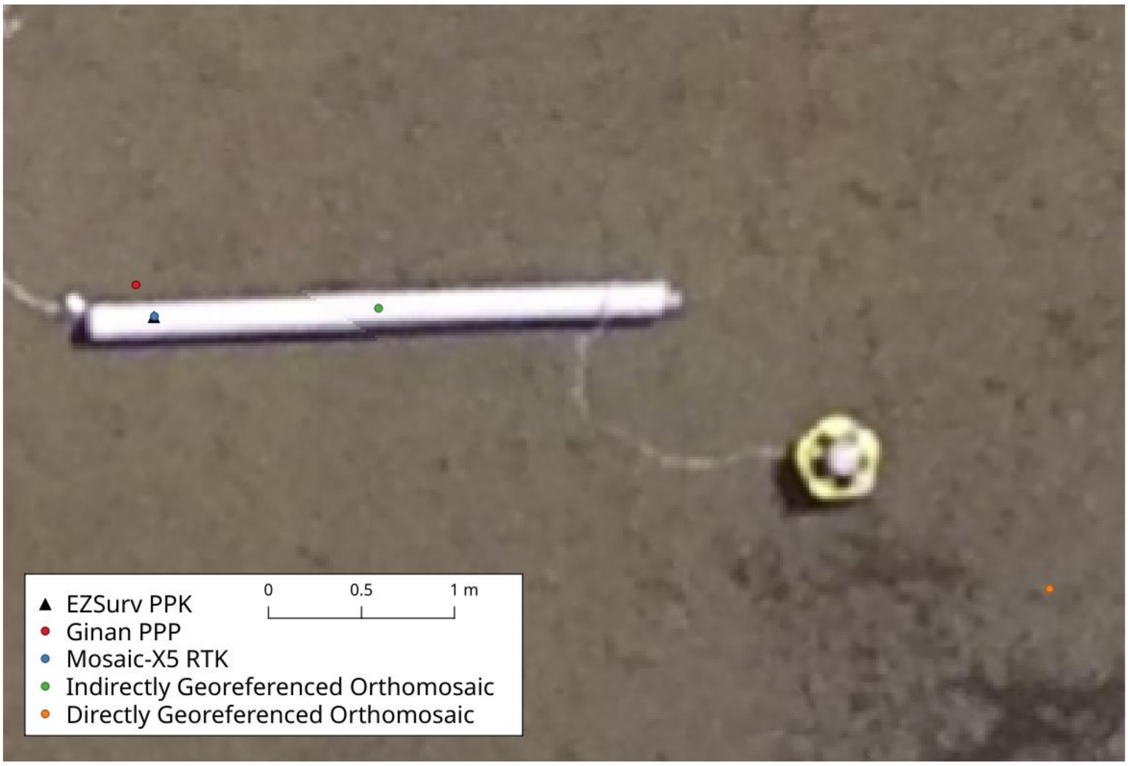

Figure 12 Map of the Test 4 Orthomosaic with each method's position overlayed.

4. Discussion

4.1. Test 1 – Ginan Convergence

During the initial equipment set up on the first day of testing, Ginan encountered issues with processing the receiver's position. It was found that the SSRA03IGS1 (Kalman Filter GPS+GLO+GAL+BDS clock combination, BNC solution) SSR corrections were performing erroneously. The PPP displacement plots in Figure 13 illustrate this, frequent spikes and dropouts are evident for each station. The SSRA03IGS1 SSR corrections were used during pre-testing in the lead up to the demonstration. Because of this, the SSRA02IGS1 SSR correction stream was adopted for the testing which does not include Beidou corrections, and as a result Beidou observations are not used by Ginan to determine position. It is likely that the lack of Beidou satellites in the Ginan solution increased convergence times across the board.

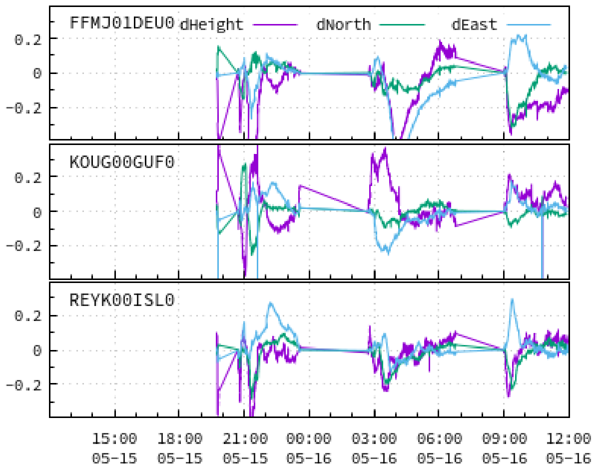

Figure 13 SSRA03IGS1 PPP Displacements (m) using BNC on 2023-05-16 (German Federal Agency for Cartography and Geodesy (BKG), 2023).

Convergence times for the Surfbee sessions in Table 4 show that all sessions converged within 50 minutes except for the horizontal component of Session 1. Shown in Figure 14, in this session both the horizontal and vertical components reach the threshold at approximately 7 minutes, but they both diverge after 5 minutes. The vertical component recovers quickly and meets the threshold, but the horizontal component slowly converges from the 40cm error level, until crossing the threshold at 1 hour 10 minutes. The horizontal component does not meet the convergence criteria because testing began before allowing the horizontal error to remain under the threshold for 10 minutes.

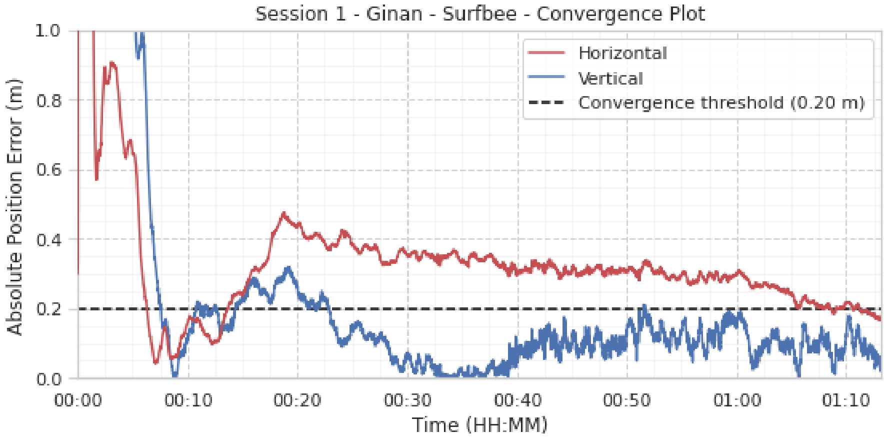

Figure 14 Session 1 - Ginan Surfbee PPP Convergence Plot.

Session 2 has the fastest overall convergence time of the Surfbee sessions, shown in Figure 15 both the horizontal and vertical components converge to under the threshold within the first 7 minutes. A spike in the vertical component is evident at 55 minutes, this occurred after the Surfbee was moved to the pontoon and the thrusters were attached and tested. During this, someone may have obstructed the antenna, which could have caused erroneous observations or loss of satellites resulting in a poor positioning solution for approximately 10 seconds.

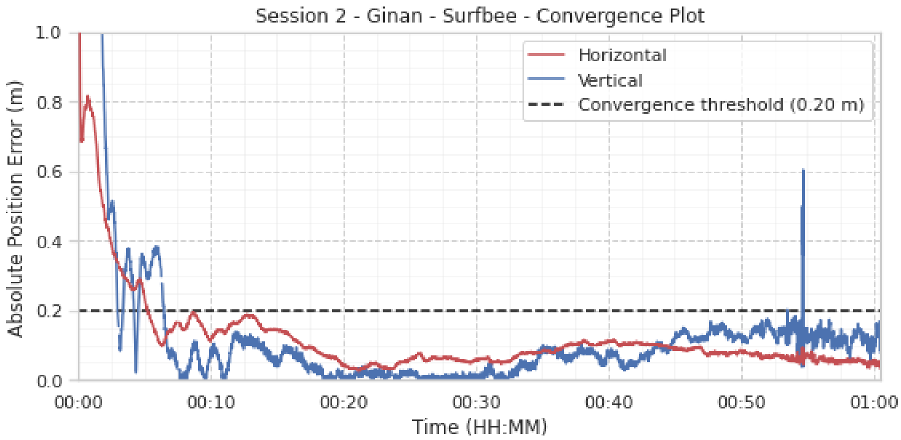

Figure 15 Session 2 - Ginan Surfbee PPP Convergence Plot.

Only two of the M600 sessions met the convergence criteria, namely Session 3 and Session 5, see Figure 16 and Figure 17 respectively. They converge at similar rates, with both components meeting the criteria at approximately 50 minutes. Overall, the poorer convergence rates for the M600 sessions could be attributed to not performing extensive pre-testing with the HC977 antenna. All pre-testing was undertaken with the TW7972 patch antennas, so the resulting Ginan configuration files may not have been suitable for the Tallysman HC977 antenna.

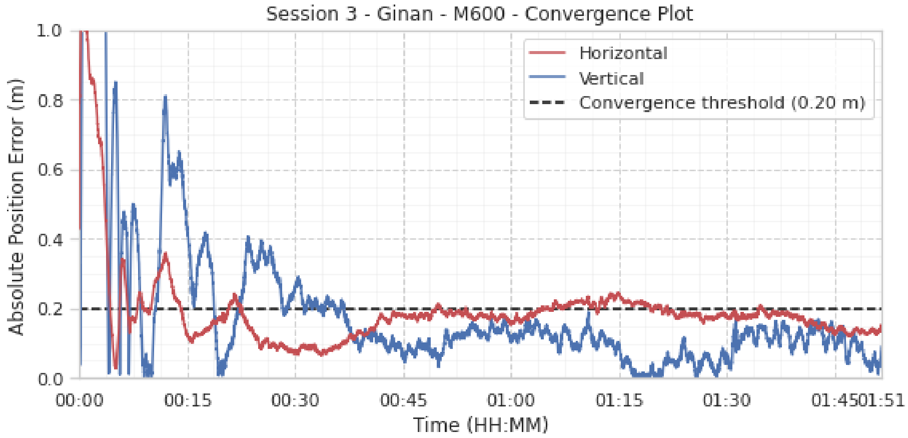

Figure 16 Session 3 - Ginan M600 PPP Convergence Plot.

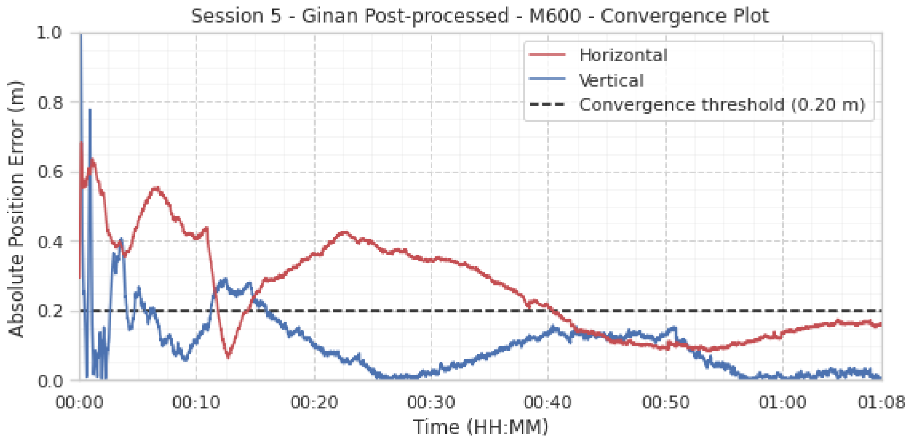

Figure 17 Session 5 - Ginan M600 PPP Convergence Plot.

Notably, across a number of both the Surfbee and M600 sessions the initial position processed by Ginan have sub-metre errors, but after subsequent iterations the positional errors increase to multiple metres. This behaviour is illustrated in the Surfbee's first session, the first minute is plotted against a logarithmic scale in Figure 18. Here we see the first three epochs have a horizontal and vertical error of approximately 0.5m which is consistent with a good SPP estimate, then the horizontal and vertical position diverges to 100m and 1000m error respectively. Ginan's output trace file for this session suggests that the initial three epochs were processed using Galileo observations only, following this GPS observations are introduced into the filter, many of which are flagged as low elevation. This is confirmed by the carrier-to-noise ratio (CNR) values from the decoded RTCM3 observations as several of the GPS L1W observations have a CNR of less than 30 dB-Hz. As with most Kalman filters, Ginan is susceptible to observation errors and outliers often caused by multipath error, so it is possible that the introduction of these low elevation or multipath GPS observations into the filter may have caused the initial positional outliers.

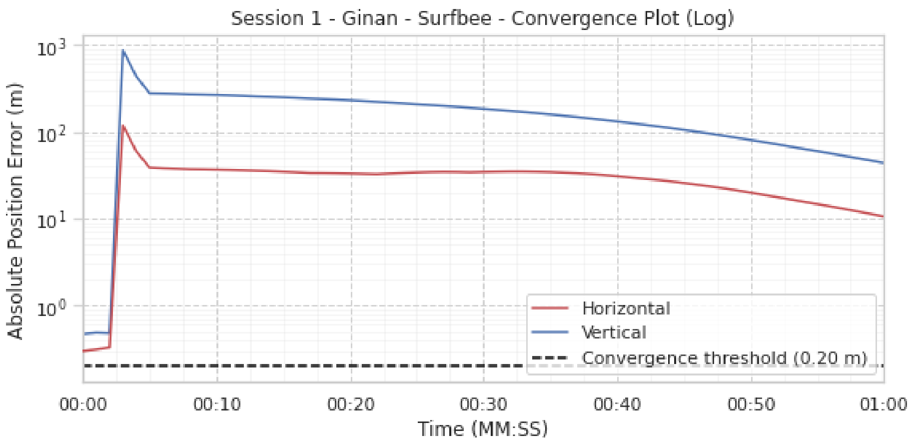

Figure 18 Session 1 - Ginan Surfbee PPP Convergence Plot – First minute on a Log scale.

4.2. Test 2 – Positioning Performance

The Surfbee's Mosaic-X5 RTK positioning performance results were consistent across all sessions, the horizontal accuracy is approximately 1cm (63.2% - 68.3% CL) and the vertical accuracy is approximately 2cm (68.3% CL). The ENU error plot for Session 4 is shown Figure 19.

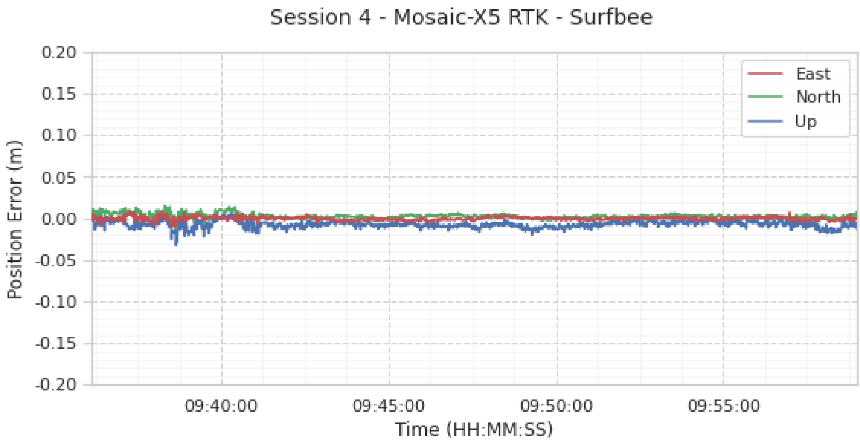

Figure 19 Session 4 - Mosaic-X5 RTK Surfbee ENU Plot.

Ginan's positioning performance onboard the Surfbee varied across each session. The most accurate session overall was Session 1, it had a horizontal accuracy of 6cm and vertical accuracy of 5cm. Interestingly, Session 1 was the only session that did not meet the convergence criteria, however as shown in the ENU plot in Figure 20 the horizontal component converges after the deployment of the Surfbee into the inshore test range. Overall, Session 3 had the poorest performance with a 25cm horizontal accuracy and a 10cm vertical accuracy. The ENU plot for the session in Figure 21 (note the increased y-axis scale) shows the horizontal component diverging approximately 20 minutes through the session.

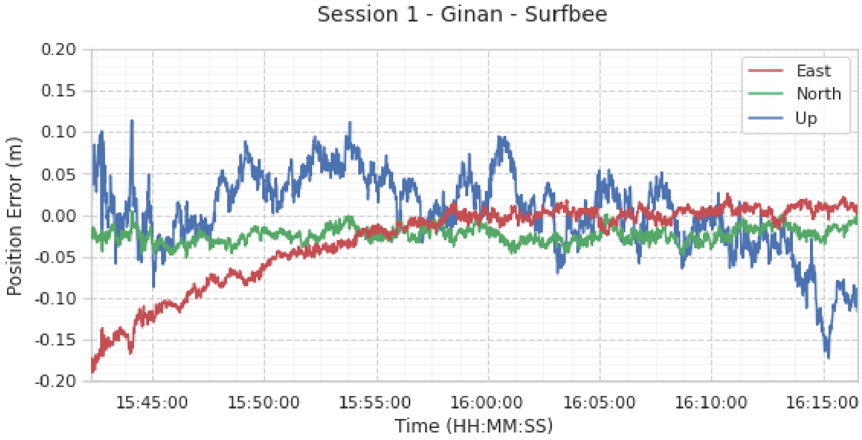

Figure 20 Session 1 – Ginan Surfbee ENU Plot.

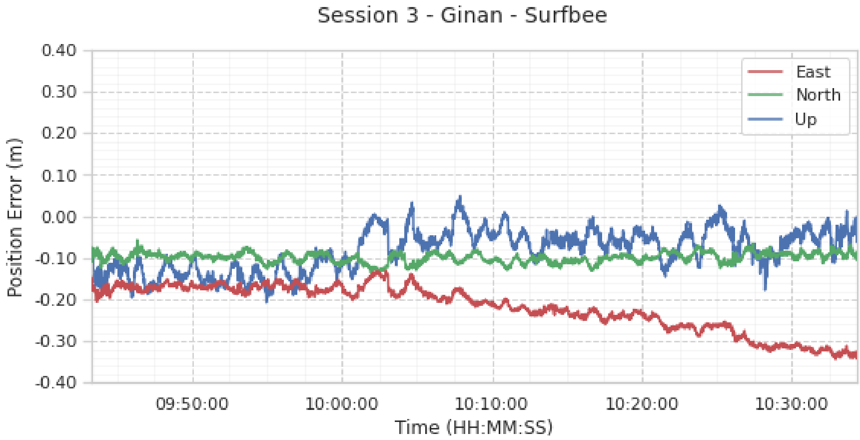

Figure 21 Session 3 – Ginan Surfbee ENU Plot.

The M600's Mosaic-X5 RTK performance was similar to that of the Surfbee's, horizontal accuracy of 1cm and a vertical accuracy of 1.5cm was seen throughout the sessions. Session 5 in Figure 22 displays the best results, although it was also one of the shortest sessions, approximately 6 minutes.

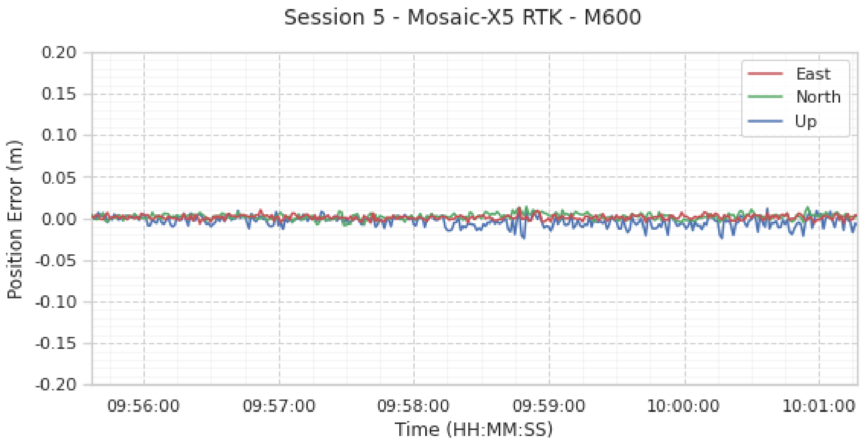

Figure 22 Session 5 – Mosaic-X5 M600 ENU Plot.

Ginan's M600 positioning performance ranges from 11-50cm accuracy in the horizontal domain and 2-50cm in the vertical domain. Session 5 shown in Figure 23 displayed the best results, with a 11cm horizontal accuracy and 2cm vertical accuracy. However, this session had to be post-processed with Ginan with the *simulate_real_time* flag enabled due to the real-time position diverging part way through the session. This was caused by the M600 kit dropping internet connection which meant that Ginan lost the BCEP and SSR correction streams and was not able to reconnect.

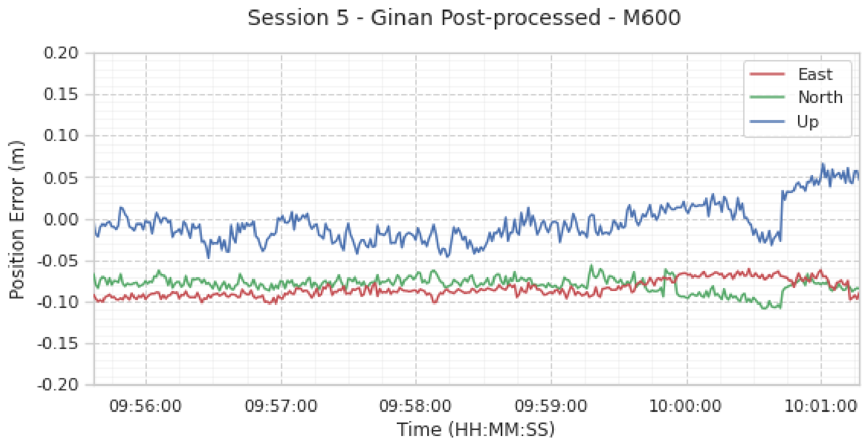

Figure 23 Session 5 – Ginan (Post-processed) M600 ENU Plot.

As expected, the poorest results are the sessions that did not successfully converge. Session 4 had a horizontal and vertical accuracy of 50cm. In this session the errors remain relatively stable, the horizontal errors are biased towards the east around 50cm and vertically the errors slowly converge from 60cm to 25cm over the session, see Figure 24.

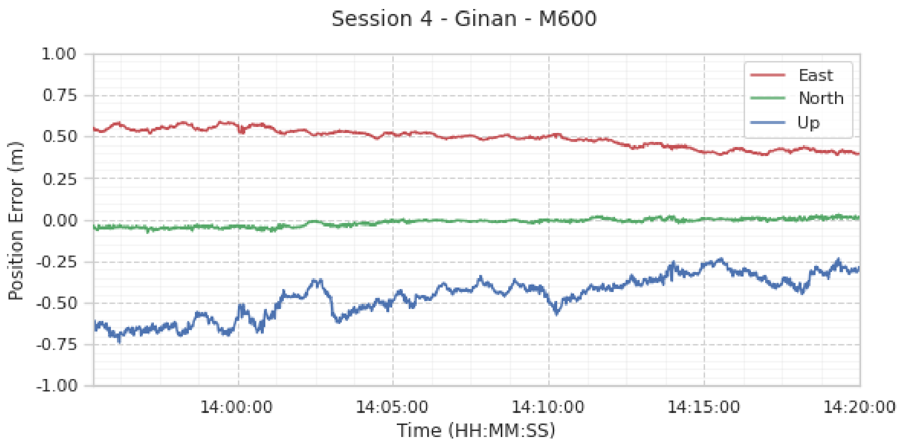

Figure 24 Session 5 – Ginan (Post-processed) M600 ENU Plot.

It is likely that the positioning performance results are biased towards the RTK sessions, ultimately resulting in a number of sessions with sub-centimetre accuracy. This is due to the fact that the Cape Ferguson CORS was used as the corrections for the RTK solution and the base station observations for post-processing the ground truth trajectories. A more rigorous ground truth could be determined from observations from an independent CORS, however the next closest AUSCORS site is Giru, located approximately 30km south of the inshore test range, and this baseline was deemed too long to be a suitable alternative.

4.3. Test 3 – Position Determination of Tracked Surface Target

The horizontal position error of the Surfbee as determined by the georeferencing methods is 3cm for the indirectly georeferenced orthomosaic and 2.6m for the directly georeferenced orthomosaic. As for the Surfbee's onboard positioning, the results are consistent with the overall positioning performance results from Test 2.

The indirectly georeferenced orthomosaic is determined from an RTK survey using the same equipment deployed on the Surfbee, as such the results are indicative of the direct georeferencing workflow using RTK. The indirectly georeferenced orthomosaic includes human error associated with pixel matching the position of each GCP in the orthomosaic, since two of the points were marked using traffic cones rather than conventional GCP targets. Furthermore, the orthomosaic is distorted by the georeferencing transformation algorithm and this has consequences on the position of the Surfbee. Different transformation algorithms introduce varying degrees of geometric distortion, depending on the number of GCPs used in the transformation. A projective algorithm was used for the processing, which allows for the correction of oblique imagery. However, if performed poorly the projective algorithm can introduce distortions to scale and parallelism as these properties are not preserved. The Surfbee's antenna position determined on the orthomosaics is also subject to uncertainties. The position of the antenna was determined by taking offset measurements in QGIS, however this does not consider the offset from the antenna's geometric centre to the antenna's phase centre.

From Table 9 we can infer that a higher accuracy onboard positioning solution could improve target position determination by up to 2.8 metres horizontally. As the Surfbee itself is 2.2 metres in length, this improvement could prevent a collision between the Surfbee and a known or detected hazard. Similarly, improving the positional accuracy of imagery produced by the M600 increases the potential to automate mapping activities in areas where survey control marks do not exist or are not able to be deployed, such as in offshore applications.

A more rigorous approach for this test would be to directly georeference the orthomosaic using the three positioning methods onboard the M600. From this, the accuracy of each orthomosaic can be computed from the errors at each GCP allowing the comparison between each method. Additionally, an error for each orthomosaic relative to the Surfbee's ground truth can be calculated. Generating imagery using a more accurate onboard position would also result in a greatly improved target position determination without requiring any external post-processing.

4.4. Test 4 – Position Determination of Surveyed Underwater Target

The underwater pipe's position was determined with a 1.2m error from the indirectly georeferenced orthomosaic and a 5m error from the directly georeferenced orthomosaic. The onboard positioning errors are consistent with the Test 3 results, although the pipe's positional error determined by Ginan is taken from Session 3, which has the poorest positioning performance of the sessions (See Figure 21) and resulted in a 20cm error from the ground truth.

For this test large uncertainty exists in the determination of the ground truth and in turn has reduced the reliability of the results. The survey of the pipe's horizontal position with the Surfbee relies on the assumption that the pipe was positioned between the centre of the buoys. Following the test, the video footage captured from the M600 confirmed that the pipe was misaligned, this is shown in Figure 25. Additionally, the buoys were constantly moving due to the tidal currents, adding further uncertainty in the survey. The M600 captured the orthomosaic of test range with the pipe during low tide, whereas the survey was performed during high tide. So, it is possible that the pipe's location may have shifted due to the tidal currents from the change in tide.

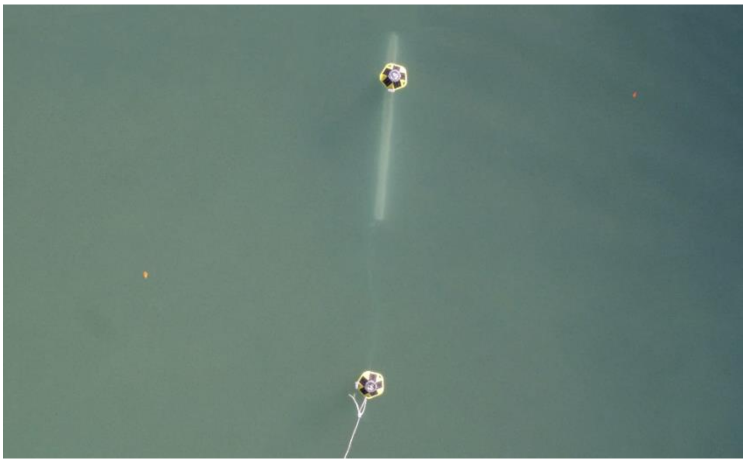

Figure 25 Location of the pipe relative to the buoys at high tide.

From Table 11 we can infer that a higher accuracy onboard positioning solution could improve target position determination by up to 4 metres horizontally, which could be a significant benefit in use cases where accurately positioning an underwater object could avoid autonomous systems colliding with hazards, or ensure safe operations in close proximity to wildlife.

Performing a more rigorous survey of the pipe would produce more reliable results. For example, equipping the Surfbee for bathymetric survey capabilities, or using down-facing cameras integrated with the existing onboard positioning systems, are potential alternatives that align with ReefWork's required capabilities. Using direct survey methods would also support an analysis on the impact of refraction on the orthomosaics. As discussed previously, directly georeferencing the images using the trajectory from each positioning method would also allow more definitive conclusions to be drawn about the accuracy of the image-based positioning approach.

4.5. Test 5 – Position Determination of Untracked Wildlife

No results are presented for Test 5, instead a discussion on developing various image-based positioning capabilities is provided in the Recommendations.

5. Recommendations

5.1. Lessons Learned

Whilst the four days of testing at the AIMS ReefWorks inshore test range was a success, several issues were faced by the project team. The issues can be broadly categorised into operational issues relating to the test plan and schedule, and technical issues relating to hardware and software problems with the equipment. This section describes some of the lessons learned from troubleshooting these issues, and recommendations for mitigation are discussed to support future testing.

Several operational issues were encountered in the implementation of the test plan, primarily impacting the schedule. Low tide occurred each day between 1:15PM and 2:40PM during the week of testing, limiting opportunities to deploy and operate the Surfbee. Some M600 test imagery was also lost due to camera and calibration faults. The testing plan was ambitious, requiring early starts and late finishes to achieve all the planned activities. Although opportunities to improve efficiency and the testing methodology were identified, ultimately all planned test scenarios were completed within the allotted time.

On the technical side, many of the issues that were faced could have been avoided by doing further pre-testing or implementing additional redundancies. The original SSR stream (SSRA03IGS1) that was used during pre-testing, and resulted in a significant loss of time on the first day of testing. This may have occurred due to the experimental nature of the IGS multi-GNSS SSR streams, however a separate multi-GNSS SSR stream from an independent analysis centre should have been tested during-pre-testing for redundancy. Similarly, the HC977 antenna used for the M600 should have been pre-tested to optimise the Ginan configuration file. Implementing these measures could have avoided some troubleshooting time and improved overall convergence times. Several power failures of the positioning equipment occurred, and it was speculated that these were caused by high accelerations, oscillations, or vibrations onboard the Surfbee and M600. The PiJuice UPS HAT includes a mobile phone battery held down by a plastic tab, but high accelerations may have caused the battery to become unseated with the battery terminals causing the RPi to reboot. As a temporary measure, the batteries were taped down, and the power issues were resolved, for a more permanent solution it is recommended that future designs of the RPi enclosure clamps down the PiJuice battery for high acceleration integrations. Internet issues also occurred throughout testing and are much more difficult to diagnose. It is believed that the internet dropouts were caused by the modems changing cell towers as the Surfbee and M600 moved around the test range. These dropouts tended to affect the Ginan position more severely, as RTKLIB will retry to connect to NTRIP casters following a disconnection by default as a result the Mosaic-X5's position would briefly drop to an RTK float solution. When Ginan lost internet connection, the filter continued estimating states with the GNSS observations, but it did not attempt to reconnect to the NTRIP caster. In the case of the Session 5 with the M600, the GNSS observations output by Ginan following the internet drop out were erroneous despite not requiring an internet connection, this may have been caused by a bug. Stress testing of the software should have identified this bug, and a wrapper script could be implemented to restart Ginan upon failure.

5.2. Precise Positioning for Marine Environments

In each of the tested scenarios with the M600 and Surfbee platforms, the RTK solution achieved and maintained real-time centimetre-level positioning accuracy both horizontally and vertically. Although RTK accuracy is dependent on the baseline distance, and requires a continuous internet connection to an NTRIP caster; RTK solutions should be considered as the primary high-accuracy correction method wherever the receiver hardware is compatible and communications can be guaranteed. Notably, all test scenarios occurred nearby to the Cape Ferguson CORS, and in areas with good cellular coverage, so further testing is recommended to determine the specific impact of longer baselines on positional accuracy, and to map the extents of the cellular coverage to ensure that accuracy requirements can be maintained for all planned test activities across the entire inshore test-range and beyond. RTK-capable GNSS hardware is generally more expensive than standalone alternatives and should be primarily considered for applications where centimetre-level accuracy is necessary.

The Ginan PPP solution performance was much more varied across the M600 and Surfbee platforms, and between each of the test scenarios. While Ginan proved capable of 5-6cm horizontal and vertical accuracy in some test sessions aboard the Surfbee and M600, the M600 deployment averaged ~20cm accuracy. Notably, this performance can be improved through further optimisation of the Ginan configuration to suit the operating environment and the capabilities of the platform's GNSS hardware. PPP remains subject to a convergence period, which was less than 50 minutes for all sessions (excluding sessions that did not converge), with some sessions converging in as little as 15 minutes. The convergence time may also be further improved through alterations to the Ginan software configurations, use of alternative corrections sources including additional satellite constellations, or further development of Ginan itself. PPP is generally a more scalable positioning technique compared to RTK, and while an internet connection is required for real-time centimetre level accuracy, PPP does not depend on simultaneous observations from a local base station, potentially making it a more suitable solution for positioning offshore. In scenarios where communications cannot be guaranteed, Ginan PPP can also be used to post-process observations, as demonstrated by the M600's Session 5 results in Test 2. Similar to RTK, PPP-capable GNSS hardware is generally more expensive than standalone alternatives.

PPK was used throughout each of the test scenarios to provide the highest quality "ground truth" available. This technique cannot be used in real-time, however it can be very useful for applications where timeliness is not relevant, and accuracy is the primary consideration. A wide range of commercial post-processing software is available, with cost-structures depending on the level of automation and additional features required by the user. With sufficient training to develop the necessary expertise to obtain the required input files, the vast majority of which are available from trusted providers for free, post-processing can be used to provide a high-accuracy solution anywhere, even offshore with requirement for cellular or internet coverage. Observations from a base station will be available for many areas of operation, including operations nearby to the Reefworks Facility, however an additional GNSS receiver deployed to log raw GNSS data can be used instead for operations where CORS data is not available. Post-processing should be explored as a foundational positioning capability, which will allow a greater understanding of the real-time performance of other positioning systems.

5.3. AIMS Capability Development

The planned capability development for ReefWorks includes the functionality of object detection and positioning from imagery and video data in both real-time and in post-processing modes. There are several requirements in this capability that can be broken down as:

- Object detection algorithms for image and video data.
- Georeferencing of images and video data from a single source.
- Georeferencing of images and video data from multiple sources.
- On-board processing on RPAS, AUV or ASV platforms.
- Data processing from multiple platforms on central system.
- Real-time data transmission from platforms to central system.
- Data storage onboard platforms.

Some commercially available solutions can meet most of these requirements, however an integrated solution is likely to require some custom development by solution providers or a third-party. A system to deliver the required capability can be adapted using commercial solutions designed for applications such as intelligence, surveillance, and reconnaissance (ISR), asset inspection, search & rescue, and surveying.

ISR covers a wide range of systems that provide a coordinated acquisition, processing, integration, and dissemination of information for situational awareness and decision making. The concept is mainly applied to defence but has applications in sectors such as law enforcement, disaster response, and critical infrastructures. RPAS solutions for autonomous inspection of powerlines, railways, and pipelines, along with other public service, mining, and civil applications, have made the operation, data acquisition and processing more accessible to a range of industry users.

These new sectors have increased the availability of commercial RPAS solutions that may be suitable for ReefWorks capability. ISR or inspection RPAS solutions vary widely according to their applications but can be summarised into three components: platforms, payloads, and software.

A range of platforms can be considered for the ReefWorks capability, such as the Height Technologies Martlet MI-3 (Height Technologies, 2023), Volarious V-LINE (Volarious, 2023), or existing DJI M600 with modified payloads. Volarious provide tethered solutions that may be suitable for the use case in the test range, however it is recommended that a requirements study be carried out to select the appropriate platform. There may be a solution that does not require a new platform, but a payload that can be integrated into existing airframes.

Dedicated ISR or inspection payloads, like the Collins Aerospace TASE Imaging System (Collins Aerospace, 2023), Overwatch Imaging PT-6 (Overwatch Imaging, 2023), Trillium Enginering HD25-XV (Trillium Engineering, 2023), or PhaseOne P3 (PhaseOne, 2023), can be integrated into multiple fixed-wing or multirotor RPAS platforms. These payloads provide multiple sensors with increased capability like stereoscopic imaging, laser range finding for real-time video georeferencing, on-board processing, and object detection. Some payloads are part of a solution ecosystem that includes software for command & control, processing, or central monitoring.

Some software solutions, like the Collins Aerospace ViewPoint, should be used together with the TASE Imaging System payload. Software solutions, like the Remote Geosystems LineVision (Remote GeoSystems, 2023), allow the integration of external data sources, payloads, and multi-domain platforms from surface vessels or subsea ROV. Some software like Axxon PSIM (Axxon, 2023), provide a solution aimed at security applications that can integrate data from images and CCTV cameras into a centralised environment. Postprocessing and visualisation can be carried out in a range of software like ESRI ArcGIS, FME, and Ocupam Geovideo. These can be used to process the data captured during this case study to produce additional positioning solutions from different integration techniques.

ReefWorks can explore several research & development opportunities in the areas of underwater positioning from terrain, visual odometry and simultaneous localisation and mapping (SLAM), cooperative positioning, and multi-sensor integration. Development in these areas would complement the off-the-shelf solutions described previously and enhance the capabilities available for ReefWorks.

6. Conclusion

Through the testing campaign conducted in collaboration with AIMS, this case study has thoroughly investigated suitable options for the provision of precise GNSS positioning for the current and future needs of AIMS. The test scenarios explored the suitability, benefits, and challenges of using of Positioning Australia products including Ginan for surveying, mapping, and positioning of objects of interest on-land, on the surface, and underwater. The case study demonstrated real-time centimetre level accuracy using a RTK solution, and centimetre to decimetre accuracy using a Ginan PPP solution, both in-flight and aboard a surface vessel in motion. RTK and Ginan were used to remotely determine the position of targets of interest using both a RPAS and ASV platforms, while also providing a comprehensive and traceable record of the movements and dynamics of the platforms across the entirety of their deployment. The performance of the RPAS and ASV research platforms was thoroughly analysed to provide recommendations on precise positioning solutions tailored towards the future capability development for the AIMS ReefWorks test ranges.

The convergence period of the Ginan PPP solution remains a challenge for some potential use cases, and further work will be required to optimise Ginan configurations to provide the best possible performance. Further development of Ginan should also address inconsistent behaviours on start-up and during longer test-sessions where the solution accuracy was inconsistent at the decimetre level. Throughout each of the tested scenarios, Ginan showed promising capability as an open-source alternative to existing precise positioning solutions, and as an all-in-one, open-source solution for operations where communications infrastructure cannot be guaranteed. This program was achieved through the collaborative integration of ReefWorks existing aerial and marine test support platforms with high-accuracy GNSS hardware and software developed by FrontierSI, with the assistance of Geoscience Australia's Ginan development team. The data collected by these platforms will be used to continue developing and improving the capabilities of Ginan.

6.1. Ginan Capability Statement

In this Case Study for the Australian Institute of Marine Science, Ginan provided real-time positioning at the centimetre to decimetre level throughout a range of test scenarios aboard an ASV and a RPAS. In scenarios where real-time positioning was not achieved, Ginan was capable of post-processing the GNSS data to determine the precise position of the research platform. Ginan's positioning capabilities were benchmarked against RTK and PPK GNSS solutions and found to provide reliable and accurate results. Ginan offers a unique capability as an open-source, all-in-one solution for real-time centimetre level positioning where communications infrastructure is available, and through its support for post-processing, offers precise positioning capability outside of communications coverage.

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Appendix

Appendix A – Equipment Shopping List

Table A1 Equipment shopping list.

Component	Source	Price (AUD)	Quantity	Platform	
				Surfbee	M600
Raspberry Pi (RPi) 4 Model B, 8GB RAM	https://au.element14.com/buy-raspberry-pi	$127.06	2	✓	✓
RPi Heatsink kit	https://core-electronics.com.au/3pc-heatsink-kit-for-raspberry-pi-4.html	$2.20	2	✓	✓
Sandisk 256GB micro SD Card	https://amzn.asia/d/7gifKq1	$47.50		✓	✓
Septentrio MosaicHAT, Mosaic-X5 variant	https://www.ardusimple.com/product/septentrio-mosaichat/	$1,125.81	2	✓	✓
Tallysman TW7972 w/ Ground Plane Triple Band GNSS patch antenna	https://au.element14.com/tallysman-wireless/33-7972-07/gnss-patch-antenna-1-557-1-606ghz/dp/3255491	$668.54	1	✓	
Tallysman HC977 Triple Band GNSS helical antenna	https://au.element14.com/tallysman-wireless/33-hc977-28/antenna-helical-1-16-1-606ghz/dp/3758289	$587.81	1		✓
SMA coaxial cable	https://au.element14.com/amphenol-rf/095-902-479-048/rf-cable-assy-sma-plug-sma-plug/dp/2857266	$76.06	2	✓	✓
SMA Female to Female adapter	https://au.element14.com/rf-solutions/adp-smaf-smaf/adaptor-sma-female-sma-female/dp/3498461	$8.44	1	✓	
SMA Male to Female right angle adapter	https://au.element14.com/siretta/adapt-smam-smaf-ra/rf-coax-adaptor-sma-male-sma-female/dp/2666791	$11.01	1		✓
Micro USB to USB A cable	https://au.element14.com/stellar-labs-computer-plus/83-16412/3-usb-a-male-to-micro-b-male-cable/dp/2802168	$2.49	4	✓	✓
PiJuice Hardware Attached on Top (HAT)	https://core-electronics.com.au/pijuice-hat.html	$109.95	2	✓	✓
DiaMec 12V 7.2Ah Sealed Lead Acid (SLA) battery	https://www.jaycar.com.au/12v-7-2ah-sla-back-up-battery-nbn-alarm-ufb/p/SB2486	$39.95	2	✓	
USB Buck Converter	https://core-electronics.com.au/5v-3a-dual-usb-step-down-buck-converter-module.html	$15.30	1	✓	
Anker 13000mAh lithium polymer (LiPo) power bank	https://amzn.asia/d/eJG42hr	$49.99	1		✓
Teltonika RUT240 4G/LTE Cellular Modem	https://powertec.com.au/buy/teltonika-rut240-compact-router-with-wifi/	$352.55	1	✓	
Teltonika power cable w/ 4-way screw terminal	https://powertec.com.au/buy/teltonika-4-pin-power-cable-with-4-way-screw-terminal/	$30.46	1	✓	
Zyxel NR2101 5G Modem	https://magnasys.tv/	$1061.50	1		✓
Blackhawk 4G Antenna	https://powertec.com.au/buy/blackhawk-adhesive-mount-antenna-698-2700mhz-for-cel-fi-go/	$27.93	2	✓	
Ethernet cable	https://au.element14.com/eaton-tripp-lite/n204-s01-bl-up/patch-cord-rj45-plug-rj45-plug/dp/3494080	$6.07	2	✓	✓
Noctua 5V 40mm Fan	https://amzn.asia/d/6SqVkwl	$35.94	1	✓	
Pelican 1400 case	https://www.pelicanstore.com.au/1400-protector-case	$244.95	1	✓	

Appendix B – MosaicHAT Configuration Files

Surfbee

```
setDataInOut, COM1, , RTCMv3+SBF+NMEA
setSBFOutput, Stream1, USB2
setSBFOutput, Stream1, ,
MeasEpoch+MeasExtra+GEORawL1+GPSNav+GPSIon+GPSUtc+GLONav+GLOTime+GALNav+GALIon+GALUtc+GALGstGps+GEONav+PVTGeodetic+ExtEvent+DiffCorrIn+ReceiverSetu
p+Commands+Comment+BDSNav+QZSNav+Meas3Ranges+BDSIon+BDSUtc
setSBFOutput, Stream1, , , msec100
setNMEAOutput, Stream1, USB1
setNMEAOutput, Stream1, , GGA+GLL+GSA+GST+GSV+RMC+VTG
setNMEAOutput, Stream1, , , msec100
setRTCMv3Formatting, ,
GPSL1CA+GPSL1PY+GPSL2PY+GPSL2C+GPSL5+GLOL1CA+GLOL2P+GLOL2CA+GLOL3+GALL1BC+GALE5a+GALE5b+GALE5+BDSB1I+BDSB2I+BDSB3I+BDSB1C+BDSB2a+QZSL1CA+QZSL2C+QZS
L5
setRTCMv3Output, COM1,
RTCM1006+RTCM1013+RTCM1019+RTCM1020+RTCM1033+RTCM1042+RTCM1044+RTCM1045+RTCM1046+RTCM1077+RTCM1087+RTCM1097+RTCM1117+RTCM1127+RTCM1230
setPVTMode, , StandAlone+DGPS+RTKFloat+RTKFixed
setSBASCorrections, S122
setSBASCorrections, , Test
setMarkerParameters, 'MOSAIC01'
setMarkerParameters, , 'FSI-M01'
setMarkerParameters, , , , 'FSI_M01'
setMarkerParameters, , , , , , , 'AU'
setObserverParameters, 'MosaicX5-01'
setObserverParameters, , 'FrontierSI'
setSignalTracking,
GPSL1CA+GPSL1PY+GPSL2PY+GPSL2C+GPSL5+GLOL1CA+GLOL2P+GLOL2CA+GLOL3+GALL1BC+GALE5a+GALE5b+GALE5+GEOL1+GEOL5+BDSB1I+BDSB2I+BDSB3I+BDSB1C+BDSB2a+QZSL1C
A+QZSL2C+QZSL5+NAVICL5
```

DJI M600

```
setDataInOut, COM1, , RTCMv3+SBF+NMEA
setSBFOutput, Stream1, USB2
setSBFOutput, Stream1, ,
MeasEpoch+MeasExtra+GEORawL1+GPSNav+GPSIon+GPSUtc+GLONav+GLOTime+GALNav+GALIon+GALUtc+GALGstGps+GEONav+PVTGeodetic+ExtEvent+DiffCorrIn+ReceiverSetu
p+Commands+Comment+BDSNav+QZSNav+Meas3Ranges+BDSIon+BDSUtc
setSBFOutput, Stream1, , , msec100
setNMEAOutput, Stream1, USB1
setNMEAOutput, Stream1, , GGA+GLL+GSA+GST+GSV+RMC+VTG
setNMEAOutput, Stream1, , , msec100
setRTCMv3Formatting, ,
GPSL1CA+GPSL1PY+GPSL2PY+GPSL2C+GPSL5+GLOL1CA+GLOL2P+GLOL2CA+GLOL3+GALL1BC+GALE5a+GALE5b+GALE5+BDSB1I+BDSB2I+BDSB3I+BDSB1C+BDSB2a+QZSL1CA+QZSL2C+QZS
L5
setRTCMv3Output, COM1,
RTCM1006+RTCM1013+RTCM1019+RTCM1020+RTCM1033+RTCM1042+RTCM1044+RTCM1045+RTCM1046+RTCM1077+RTCM1087+RTCM1097+RTCM1117+RTCM1127+RTCM1230
setPVTMode, , StandAlone+DGPS+RTKFloat+RTKFixed
setSBASCorrections, S122
setSBASCorrections, , Test
setReceiverDynamics, High
setReceiverDynamics, , UAV
setMarkerParameters, 'MOSAIC02'
setMarkerParameters, , 'FSI-M02'
setMarkerParameters, , , , 'FSI_M02'
setMarkerParameters, , , , , , , 'AU'
setObserverParameters, 'MosaicX5-02'
setObserverParameters, , 'FrontierSI'
setSignalTracking,
GPSL1CA+GPSL1PY+GPSL2PY+GPSL2C+GPSL5+GLOL1CA+GLOL2P+GLOL2CA+GLOL3+GALL1BC+GALE5a+GALE5b+GALE5+GEOL1+GEOL5+BDSB1I+BDSB2I+BDSB3I+BDSB1C+BDSB2a+QZSL1C
A+QZSL2C+QZSL5+NAVICL5
```

Appendix C – Ginan Configuration Files

Surfbee

```
# PEA configuration for real-time multi-GNSS PPP solution for Surfbee kinematics
inputs:
    root_directory: ./data/input/
    atx_files:      [ igs14.atx ]
    blq_files:      [ OLOAD_GO.BLQ ]
    snx_files:      [ meta_gather_20210721.snx, tables/igs_satellite_metadata_2219_plus.snx ]
    egm_files:      [ tables/EGM2008.gfc ]
    tide_files:     [ tables/fes2014b_Cnm-Snm.dat ]
    satellite_data:
        inputs_root: "https://<USER>:<PASS>@ntrip.data.gnss.ga.gov.au/"
        rtcm_inputs:
            - BCEP00BKG0
            - SSRA02IGS0
    troposphere:
        gpt2grid_files: gpt_25.grd
    gnss_observations:
        rtcm_inputs:
            - serial:///dev/ttyAMA0  # RTCM via serial port (Septentrio Mosaic-X5)
outputs:
    root_directory: ./data/output/ppp/
    trace:
        output_stations:    true
        output_network:     false
        level:              1
        network_filename:   $DATETIME_network.TRACE
        station_filename:   $DATETIME-<CONFIG>_station.TRACE
        output_residuals:   true
        output_config:      true
    decoded_rtcm:  # JSON file containing all decoded RTCM3 things
        output:     true
        filename:   $DATETIME-<CONFIG>_decoded_rtcm.json
    rinex_nav:  # RINEX format navigation file
        output:     true
        filename:   $DATETIME-BRDC_<SYS>.rnx
    rinex_obs:  # RINEX format obs file
        output:     true
        filename:   $DATETIME-<CONFIG>_<SYS>.rnx
    rtcm_nav:  # RTCM3 BCEP and SSR streams
        output:     true
        filename:   $DATETIME-<STREAM>_NAV.rtcm3
    rtcm_obs:  # RTCM3 observation streams
        output:     true
        filename:   $DATETIME-<CONFIG>_OBS.rtcm3
    sp3:  # SP3 SSR ephemeris file
        output:             true
        filename:           $DATETIME.sp3
        data_source:        SSR
        output_interval:    1
    clocks:  # SSR clock file
        output:             true
        filename:           $DATETIME.clk
        receiver_source:    NONE
        satellite_source:   SSR
    gpx:  # GPX coordinate output
        output:     true
        filename:   $DATETIME-<CONFIG>.gpx
    ppp_sol:  # PPP solution output
        output:     true
        filename:   $DATETIME-<CONFIG>.pppsol
    metadata:
        config_description: Surfbee
mongo:
    enable:                 true
    output_measurements:    true
    output_states:          true
    uri:                    mongodb://mongo:27017
    database:               ginan
processing_options:
    process_modes:
        ppp:    true
    ssr_inputs:
        ssr_antenna_offset:         APC
        validity_interval_factor:   18.0
    epoch_control:
        require_obs:            false
        epoch_interval:         1
        epoch_tolerance:        0.5  # 1Hz RTCM data rate
        wait_next_epoch:        1
        wait_all_stations:      1
        assign_closest_epoch:   true
        simulate_real_time:     false
    gnss_general:
        elevation_mask:         10
        rec_reference_system:   gps
        raim:                   true
        max_gdop:               30
        sys_options:
```

```yaml
            gps:
                process:                true
                ambiguity_resolution:   true
                zero_receiver_dcb:      true
                clock_codes: [  L1C, L2W  ]
                code_priorities: [  L1C, L2W, L5Q  ]
            gal:
                process:                true
                ambiguity_resolution:   true
                zero_receiver_dcb:      true
                code_priorities: [  L1C, L5Q, L1X, L5X, L7Q  ]
            bds:
                process:                true
                ambiguity_resolution:   true
                zero_receiver_dcb:      true
                reject_eclipse:         true
                code_priorities:        [ L2I, L6I ]
    gnss_models:
        troposphere:
            model:  gpt2
        ionospheric_component:
            enable: true
            automatic_def_codes:    false
            common_ionosphere:      true
            use_if_combo:           True
        sat_pos:
            source: ssr
    model_error_checking:
        ambiguities:
            outage_reset_limit:     100
            phase_reject_limit:     10
            reinit_on_all_slips:    true
        deweighting:
            deweight_factor:    10000
    ambiguity_resolution:
        elevation_mask:             10
        max_rounding_iterations:    3
        wide_lane:
            mode:                       iter_rnd
            success_rate_threshold:     0.9999
            solution_ratio_threshold:   3
            process_noise_sat:          0.00001
            process_noise_rec:          0.0001
        narrow_lane:
            mode:                       lambda_bie
            success_rate_threshold:     0.9999
            solution_ratio_threshold:   3
    filter_options:
        outlier_screening:
            max_filter_iterations:  20
            max_prefit_removals:    2
estimation_parameters:
    stations:
        error_model:    elevation_dependent
        code_sigmas:    [0.35]
        phase_sigmas:   [0.0035]
        pos:  # Position
            estimated:      [true]
            sigma:          [5]
            proc_noise:     [0]  # Max speed in m/s
            proc_noise_dt:  second
        pos_rate:  # Velocity
            estimated:      [true]
            sigma:          [0.1]
            proc_noise:     [1]  # Max acceleration in m/s2 - higher value equals more smoothing
        clk:  # Clocks
            estimated:      [true]
            sigma:          [100]
            proc_noise:     [10]
        amb:  # Integer phase ambiguities
            estimated:      [true]
            sigma:          [1000]
            proc_noise:     [0]
        trop:  # Zenith wet delay
            estimated:      [true]
            sigma:          [0.3]
            proc_noise:     [0.0001]
            proc_noise_dt:  second
        trop_grads:  # Azimuthal components of tropospheric mapping functions
            estimated:      [true]
            sigma:          [0.02]
            proc_noise:     [1.0E-6]
            proc_noise_dt:  second
        ion_stec:  # Ionosphere
            estimated:      [true]
            sigma:          [100]
            proc_noise:     [10.0]
        code_bias:  # Code bias
            estimated:      [true]
            sigma:          [10]
            proc_noise:     [0]
```

DJI M600

```yaml
# PEA configuration for real-time multi-GNSS PPP solution for DJI M600 kinematics
inputs:
    root_directory: ./data/input/
    atx_files:      [ igs14.atx ]
    blq_files:      [ OLOAD_GO.BLQ ]
    snx_files:      [ meta_gather_20210721.snx, tables/igs_satellite_metadata_2219_plus.snx ]
    egm_files:      [ tables/EGM2008.gfc ]
    tide_files:     [ tables/fes2014b_Cnm-Snm.dat ]
    satellite_data:
        inputs_root: "https://<USER>:<PASS>@ntrip.data.gnss.ga.gov.au/"
        rtcm_inputs:
            - BCEP00BKG0
            - SSRA02IGS0
    troposphere:
        gpt2grid_files: gpt_25.grd
    gnss_observations:
        rtcm_inputs:
            - serial:///dev/ttyAMA0  # RTCM via serial port (Septentrio Mosaic-X5)
outputs:
    root_directory: ./data/output/ppp/
    trace:
        output_stations:    true
        output_network:     false
        level:              1
        network_filename:   $DATETIME_network.TRACE
        station_filename:   $DATETIME-<CONFIG>_station.TRACE
        output_residuals:   true
        output_config:      true
    decoded_rtcm:  # JSON file containing all decoded RTCM3 things
        output:     true
        filename:   $DATETIME-<CONFIG>_decoded_rtcm.json
    rinex_nav:  # RINEX format navigation file
        output:     true
        filename:   $DATETIME-BRDC_<SYS>.rnx
    rinex_obs:  # RINEX format obs file
        output:     true
        filename:   $DATETIME-<CONFIG>_<SYS>.rnx
    rtcm_nav:  # RTCM3 BCEP and SSR streams
        output:     true
        filename:   $DATETIME-<STREAM>_NAV.rtcm3
    rtcm_obs:   # RTCM3 observation streams
        output:     true
        filename:   $DATETIME-<CONFIG>_OBS.rtcm3
    sp3:  # SP3 SSR ephemeris file
        output:             true
        filename:           $DATETIME.sp3
        data_source:        SSR
        output_interval:    1
    clocks:  # SSR clock file
        output:             true
        filename:           $DATETIME.clk
        receiver_source:    NONE
        satellite_source:   SSR
    gpx:  # GPX coordinate output
        output:     true
        filename:   $DATETIME-<CONFIG>.gpx
    ppp_sol:  # PPP solution output
        output:     true
        filename:   $DATETIME-<CONFIG>.pppsol
    metadata:
        config_description: m600
mongo:
    enable:                 true
    output_measurements:    true
    output_states:          true
    uri:                    mongodb://mongo:27017
    database:               ginan
processing_options:
    process_modes:
        ppp:    true
    ssr_inputs:
        ssr_antenna_offset:         APC
        validity_interval_factor:   18.0
    epoch_control:
        require_obs:            false
        epoch_interval:         1
        epoch_tolerance:        0.5  # 1Hz RTCM data rate
        wait_next_epoch:        1
        wait_all_stations:      1
        assign_closest_epoch:   true
        simulate_real_time:     false
    gnss_general:
        elevation_mask:         10
        rec_reference_system:   gps
        raim:                   true
        max_gdop:               30
        sys_options:
            gps:
                process:                true
                ambiguity_resolution:   true
                zero_receiver_dcb:      true
```

```yaml
                clock_codes: [  L1C, L2W  ]
                code_priorities: [  L1C, L2W, L5Q  ]
            gal:
                process:                true
                ambiguity_resolution:   true
                zero_receiver_dcb:      true
                code_priorities: [  L1C, L5Q, L1X, L5X, L7Q  ]
            bds:
                process:                true
                ambiguity_resolution:   true
                zero_receiver_dcb:      true
                reject_eclipse:         true
                code_priorities:        [ L2I, L6I ]
    gnss_models:
        troposphere:
            model:  gpt2
        ionospheric_component:
            enable: true
            automatic_def_codes:    false
            common_ionosphere:      true
            use_if_combo:           True
        sat_pos:
            source: ssr
    model_error_checking:
        ambiguities:
            outage_reset_limit:     100
            phase_reject_limit:     10
            reinit_on_all_slips:    true
        deweighting:
            deweight_factor:    10000
    ambiguity_resolution:
        elevation_mask:             10
        max_rounding_iterations:    3
        wide_lane:
            mode:                       iter_rnd
            success_rate_threshold:     0.9999
            solution_ratio_threshold:   3
            process_noise_sat:          0.00001
            process_noise_rec:          0.0001
        narrow_lane:
            mode:                       lambda_bie
            success_rate_threshold:     0.9999
            solution_ratio_threshold:   3
    filter_options:
        outlier_screening:
            max_filter_iterations:  20
            max_prefit_removals:    2
estimation_parameters:
    stations:
        error_model:    elevation_dependent
        code_sigmas:    [0.35]
        phase_sigmas:   [0.0035]
        pos:  # Position
            estimated:      [true]
            sigma:          [5]
            proc_noise:     [0]  # Max speed in m/s
            proc_noise_dt:  second
        pos_rate:  # Velocity
            estimated:      [true]
            sigma:          [0.1]
            proc_noise:     [3]  # Recommended to use 1/4th of max acceleration in m/s2 - higher value equals more smoothing
        clk:  # Clocks
            estimated:      [true]
            sigma:          [100]
            proc_noise:     [10]
        amb:  # Integer phase ambiguities
            estimated:      [true]
            sigma:          [1000]
            proc_noise:     [0]
        trop:  # Zenith wet delay
            estimated:      [true]
            sigma:          [0.3]
            proc_noise:     [0.0001]
            proc_noise_dt:  second
        trop_grads:  # Azimuthal components of tropospheric mapping functions
            estimated:      [true]
            sigma:          [0.02]
            proc_noise:     [1.0E-6]
            proc_noise_dt:  second
        ion_stec:  # Ionosphere
            estimated:      [true]
            sigma:          [100]
            proc_noise:     [10.0]
        code_bias:  # Code bias
            estimated:      [true]
            sigma:          [10]
            proc_noise:     [0]
```

Appendix D – Ground Control Points

Table D1 Ground control points GDA2020 coordinates.

GCP	Registered Mark No.	Name	GDA2020		
			Latitude	Longitude	Ellipsoid Height
1	112148	Granite Rock West Steel Bolt	-19.27662355	147.0581811	62.4077
2	112147	Granite Rock East Steel Bolt	-19.2762817	147.05886336	63.3512
3	N/A	Jetty Painted White Cross	-19.27768566	147.05910032	62.4056
4	N/A	Wharf Painted White Cross	-19.27738714	147.05866943	61.9305

Table D2 Ground control points MGA2020 coordinates.

GCP	Registered Mark No.	Name	MGA2020 Zone 55		
			Easting	Northing	AHD Height[1]
1	112148	Granite Rock West Steel Bolt	506113.3652	7868563.2789	3.7907
2	112147	Granite Rock East Steel Bolt	506185.0666	7868601.0763	4.7342
3	N/A	Jetty Painted White Cross	506209.912	7868445.7233	3.7886
4	N/A	Wharf Painted White Cross	506164.6479	7868478.7701	3.3135

1. AHD heights derived from AUSGeoid2020.

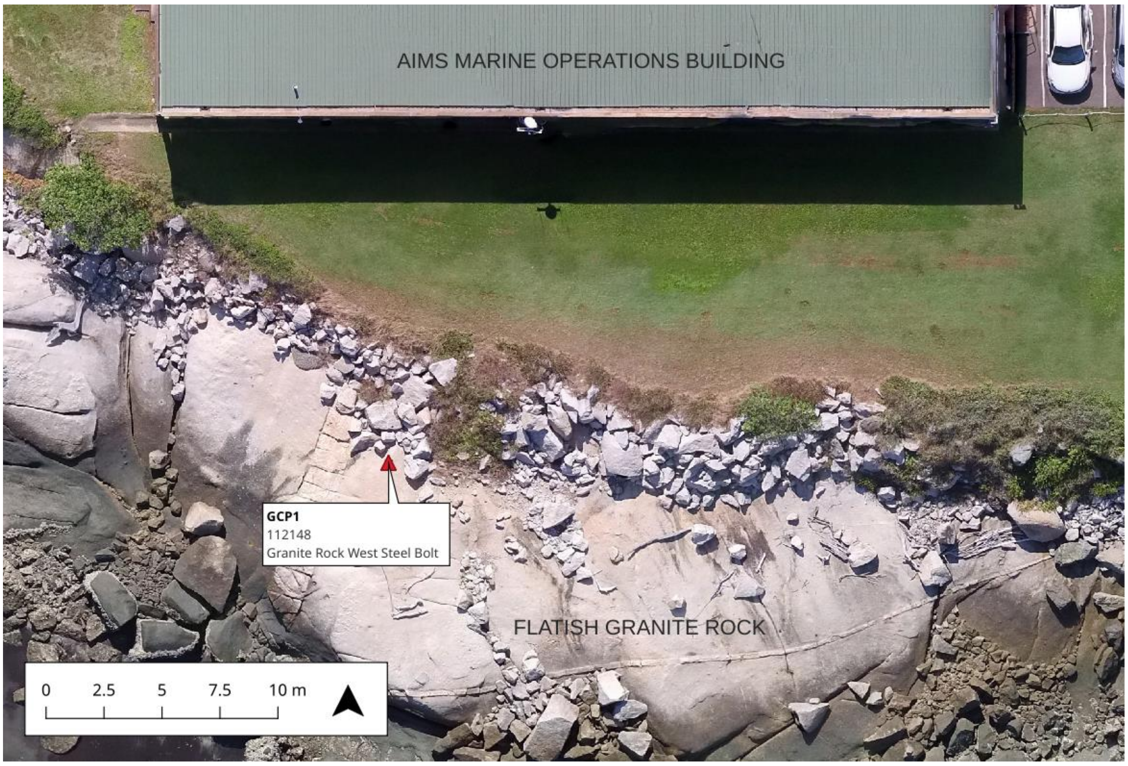

Figure D1 Ground control point 1 map.

Figure D2 Ground control point 2 map.

Figure D3 Ground control point 3 map.

Figure D4 Ground control point 4 map.