Collaborative PNT NATO Demo

Dr. Mikel M Miller
704 Persimmon Way
Niceville, FL 32578
USA

Mikel.Miller@is4s.com

ABSTRACT

Global Navigation Satellite Systems (GNSS) are used throughout the NATO forces but the availability of GNSS signals in contested environments due to signal jamming, obstruction, or spoofing is a subject of great concern. The Research Task Group (SET-229) on "Cooperative Navigation in GNSS Degraded / Denied Environments" was formed to focus on how to enhance NATO effectiveness through the improved use of advanced, cooperative/collaborative Position, Navigation, and Time (PNT) technologies and techniques. The SET-229 demonstrated complementary PNT technologies in a typical Search and Recovery (SAR) operation conducted in a GNSS degraded/denied environment.

This paper summarizes the demonstration which includes:

- *A description of the simulated Search and Recovery (SAR) mission in a GNSS degraded/denied environment.*
- *A technical overview/description of emerging cooperative / collaborative PNT sensor and system technologies and techniques employed before and during the simulated SAR mission.*

The paper also includes descriptions of various PNT technologies that complement Global Navigation Satellite Systems (GNSS) receivers. In addition, an innovative low-cost Software Defined Radar provided real-time Situational Awareness (SA) of "Blue (Friend)" and "Red (Foe)" forces to the Mission Command Center (MCC). An additional SA enhancement was the implementation of a low-cost GNSS SA system using cell phones to provide the MCC with real-time GNSS jamming information SA continuously during the SAR demonstration. The paper describes the advantages obtained by implementing the latest non-GNSS PNT technologies and cooperatively / collaboratively leveraging various PNT information from disparate users and sensors. It explores the enhanced capabilities that will result, such as higher situational awareness, greater mission effectiveness, more reliable navigation and reporting for operations in urban and indoor environments and enhanced unmanned-platform navigation.

1.0 DEMONSTRATION BACKGROUND, GOALS AND OBJECTIVES, AND RELEVANCE

1.1 Background

Position, Navigation, and Timing (PNT) services provided by Global Navigation Satellite Systems (GNSS) are used throughout NATO forces on a daily basis. GNSS has forever changed the way NATO forces train and execute their missions thanks to its unprecedented availability, accuracy, and precision. Because of GNSS's great success, threats to NATO forces have developed jamming and spoofing techniques to limit and/or remove GNSS PNT information to/from the NATO PNT user. The NATO Science and Technology Organization (STO) is very interested in complementary PNT technologies and techniques to enable robust and resilient PNT operations in GNSS degraded / denied environments. Indeed, there have been numerous NATO study groups, symposia, and recommendations presented during the last 20 years regarding GNSS enhancements and complimentary PNT technologies. The Research Task Group (SET-229) on "Cooperative Navigation in GNSS Degraded / Denied Environments" was formed to focus on how to enhance NATO effectiveness through the improved use of advanced, cooperative/collaborative PNT technologies and techniques. This paper summarizes the work of the RTG, includes a description of the technology demonstration (Search and Recovery (SAR) in a GNSS degraded/denied environment) and provides a technical overview of new and emerging cooperative / collaborative sensor and system technologies that will impact future NATO operations world-wide.

1.2 Goals and Objectives

SET-229 was formed to:

- Explore cooperative navigation technologies and techniques for interoperating personnel and platforms to maintain accurate and reliable navigation in GNSS degraded/denied environments.
- Develop cooperative PNT and situational awareness (SA) sensor suites and algorithms to enable collaborative/cooperative PNT with systems developed by other nations.
- Demonstrate these PNT systems in a SAR Mission in a GNSS degraded/denied environment.

1.3 Relevance

Modern Military forces are heavily reliant on precision PNT to execute their missions. In a GNSS degraded or denied environment this cannot be guaranteed with currently deployed systems, particularly when GNSS is used as the primary positioning system. Accurate PNT knowledge is fundamental for maintaining situational awareness, locating threats, identifying and protecting friendly forces, and optimally deploying assets. Current military PNT is mainly provided by GPS, which is under a growing threat of intentional (jamming and spoofing) and unintentional threats. Unintentional GNSS threats (multipath, shading etc.) are present during operations in urban, indoor, subterranean and underwater environments. In such environments, it may be difficult for NATO forces to gain access to the battlespace and successfully conduct operations. These GNSS threat environments require the need for robust, resilient, and accurate PNT systems that can operate in GNSS degraded or denied environments. Robust, resilient, and accurate PNT information is critical to ensure mission effectiveness, minimize casualties and collateral effects. To maintain PNT capabilities in the Anti-Access/Area Denial (A2/AD) environments, new PNT sensors and techniques are required. The aim of SET-229 was to employ Cooperative navigation techniques to mitigate the GNSS threat by sharing information between interoperating systems in a manner that provides improved navigational capabilities.

2.0 SEARCH AND RECOVERY (SAR) DEMONSTRATION OVERVIEW:

The following sections describe the SAR Demonstration. The rehearsal trial occurred in May/June 2019 and the final demonstration was conducted on 16 Aug 2019. A quad-copter was used to captured high resolution video imagery of the range in order to process into a situational awareness backdrop for the demonstration trial.

2.1 Simulated Environment/Location

The Test Site (see Figure 1) provided a realistic environment with several key features including a forest canopy, urban operations, raining weather and the ability to accomplish GNSS Jamming.

Figure 1: AR demonstration site.

2.2 Mission Overview

A realistic Search and Recovery mission was chosen to demonstrate "Cooperative / Collaborative PNT in a GNSS Contested Environment". The mission was broken down in 6 phases. The 1st 2 phases involved mapping the outdoor and indoor areas where the SAR mission would occur and are summarized in Table 1.

Phase 1: Mapping the overall SAR mission area using Cooperative Arial Mapping and Modelling.

Phase 2: Mapping the interior of the buildings where the Recovery Item was being kept and where the overwatch teams would conduct their missions.

Table 1 highlights the Mission Phase, Actions, Equipment, Country, Collaboration, Products Produced, and the Phase Goals. With the SAR outdoor / indoor areas mapped and the hostage localized to a building in the village, the SAR mission was ready for execution.

The SAR Mission OV-1 is shown in Figure 2. Table 2 summarizes the planned 4 phases of the SAR mission; highlighting the same information as Table 1. Table 3 provides, in detail, the actual SAR events that took place the day of the official NATO Demonstration

Table 1: Pre-mission phases: 1 – outdoor mapping; 2 – indoor mapping.

Phase	Mission	Actions	Equipment	Collaboration	Product	Goals
1	Cooperative Aerial Model	Geo-referenced photo reconaissnace Time required: 4 hours - setup, data collection and processing	1. Quad-Rotor platform or equilivent with RGB camera with internal nav system 2. Position GNSS Survey System 3. Laptop with AGISoft Photogramaphy s/w 4. Dismount PNT s/w	Teams will map sections and results will be integrated to create a single areal map of the area This map will be used by ground teams/command center and s/w defined radar survellance system	Integrated Digital Terrain Model (DTM) which produces the visual aerial map on the command screen	Aerial images from (multiple) UAVs post processed and merged to form comprehensive area model
2	Cooperative Indoor Mapping with Map Updates	Create indoor point cloud Overlay indoor point cloud model/map onto Aerial Model/map Leverage Phase 1's aerial maps to provide geo-referenced building dimensions Time required: 8 hours - setup, data collection and processing	***Sensors:*** 1. Vision System with integtrated with IMU 2. TRX system 3. Visual Odometry (optional) ***Platforms*** : 1. Dismounts 2. UGV ***Software*** : Mapping/visualization s/w	Teams will model/map interior and results will be integrated to create a single indoor model/map of buildings	Integrated indoor/outdoor model/map	Indoor model/maps from multiple sources post processed and merged to form comprehenive geo-referenced 2D indoor/outdoor model/map Video playback demonstrating 3D point cloud being created of bulding interior

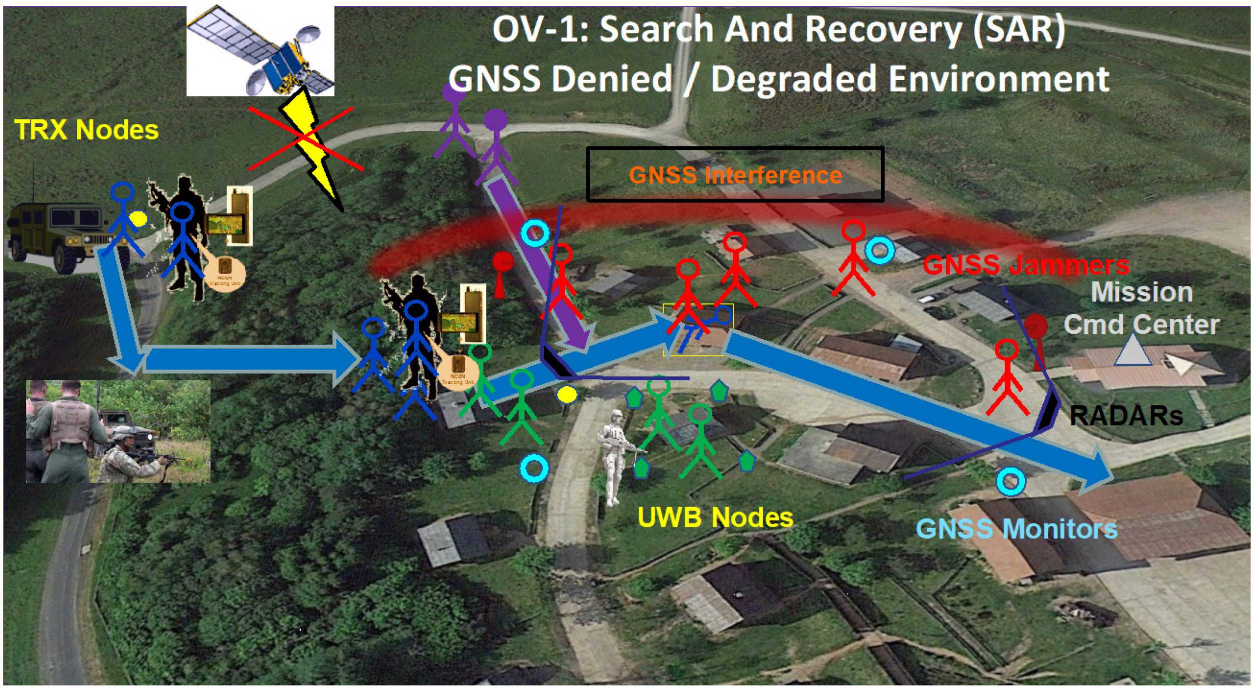


Figure 2: Search and Recovery Mission (SAR) – Operational View (OV-1).

Table 2: SAR Mission Phases (3-5: SAR mission staging & PNT “error reset”; 6: Recovery Sequence).

Phase	Mission	Actions	Equipment	Collaboration	Product	Goals
3	Transport SAR team to drop off Point A outside the village	Simulated SAR Team Vehicle with laser & camera enabling navigation to rescue site in GNSS denied environment Rover with tethered (hovering) UAV provides SA (optional) Ground based Radar provides SA Release UGVs	1. Up to 2 vehicles with LADARs integrated with an IMU - optional camera 2. Quad rotor for overview UGV 3. IMU reference system 4. S/W Defined Radar 5. Local Area Wifi	Colloboration between transport vehicles and UAV (comm link - wifi) Track (SA) transport team vehicle and personnel with pre-set radar tracking system and rover with tehtered UAV	RT display of Rescue team movement displayed in command post and to team members	SAR team SA for both the team and the command center in RT
4	SAR team PNT ‘error reset’ in GNSS Degraded/Denied Environment - still at Point A	Ground vehicle with AJ capability that provides PNT initialization data to SAR team - Simulated Comm link between Vehicle to SAR Team providing PNT initialization data UWB users will manually enter initial position off the base stations	***SAR Team*** : Dismount PNT System & Comm Radios - TRX PNT System — Comm Radios - UWB PNT System - Foot mounted PNT system - Vision odometry system ***Command Center display and software***	Simulated mounted vehicle with accurate PNT provides initilization data to dismounts	Initialization Data - Simulated	Successful PNT initialization to dismounts - simulated
5	Dismounted SAR teams will leave the vehicle (Point A) and move to the entry point outside the forest (Point B). BF / RF ID & Tracking will occur and be presented in RT in the Command Center	- UWB base stations provide RT dismount localization within the perimeter of the building - TRX system will also provide RT dismount localization throughout the mission - Outdoor FMCW wideband radar provides dismount (BF/RF) tracking outdoors - Visual tracking from UAV	***SAR Team*** : Dismount PNT System & Comm Radio TRX PNT System — Comm Radios - UWB PNT System - Foot mounted PNT system - Vision odometry system - Software Defined Radars for Personnel Tracking ***Command post equipment***	‘- Each Team provides tracking info using their technology / techniques ‘- Data is merged into the Command Center RT Display	RT display of SAR team movement displayed in command post and to team members BF & RF tracking displayed on Command Screen	BT and RT members succesfully tracked throughout rescue mission using at least one system
6	SAR Sequence: 1. Travel through Forest to edge of village. 2. Overwatch team travels to building 16: - Secures building - Positions team to provide overwatch during mission 3. SAR team travels to building 20: - TM 1 enters building and starts clearing floors - starting at the bottom - TM 2 moves directly to suspected room with object - TM1 meets TM2 with Recovery Object and exit the building 4. TM1 meets TM2 with hostage and exits the building 5. SAR teams move to Church 6. Mission over	See SAR Mission Discription for sequence of events Command Center Actions: - RT display of all BF and RF activities during the SAR operations - Personnel trackers are providing RT location data to Command Center to give SA to commander - Radar data is providing RT SA of any movement in the village - RT display of GNSS jamming environment	See 5 above	See 5 Above	See 5 Above	

Table 3: Actual SAR events that took place the day of the official NATO Demonstration.

Mission Time	Mission	Actions	Mission Copmmand & Control (C2) Center
13:25		**SAR Mission in GNSS Degraded/Denied Environment**	
0.00	SAR Team (ST) 1 to drop off Point A outside the village Other STs to their in-theatre staging positions	1) MC instructs STs to begin Mission 2) ST-1 moves to Point A 3) All other dismounted STs move to their staging pc	Transmit data in RT to command center for display
0.50	ST-1	ST-1 moves around the vehicle twice to set heading	
1.50	ST-1 moves to Point B		
4.00	Mission in-theatre staging	1) Dismounted STs in place 2) ST-2 & ST-3 at Point B. 3) ST-1 move to Point B 4) ST-2 & ST-3 move to Building 16 and secure	
5.50	ST-2 & ST-3 Secure the Building	Clear building at get into overwatch position Radio Call - "All set"	
6.50	SAR Phase	ST-1 moves to Bldg 20 - 10 sec ST-1-1 enters first and clears bottom floor ST-1-2 immediately goes to suspected hostage location ST-12 communicates when recovery has occured - "The Tea is ready" ST-4 moves from Point C to Bldg 20 when ST-1 enters	
8.00	Travel to Barn for exfill	ST-1 meets ST-4 outside door and travels to BARN ST-1 radios MC to inform them they are out of the building and heading to the BARN (Exfil point). "The cup is empty." MC radios T&G - all clear so they may exit 16 and come to the BARN	
9.00	***End of Rescue Mission***		

2.3 GNSS Jamming

Flexible GNSS jamming from two fixed locations within the test site; one just outside the church and the other just outside building 20 (the building containing the ‘Recovery Object’). The outdoor signal generators were remotely controlled from inside the Mission Control room in church via a lap-top PC. Several power settings were determined in collaboration with the GNSS Situational Awareness (SA) team, to enable them to show their detection system transition from no jamming, through partially jamming and into completely jamming.

2.4 SAR Mission Command and Control (C2) Center

To provide real-time “live” information to the SAR Mission Command & Control (C2) Center, the Croatian team put together the network infrastructure and Command Center Display software to present all the different Cooperative PNT technology outputs to the demonstration audience - see Figure 3.

Figure 3: Map screen of the demo range in the Mission C2 Center software with satellite image in the back and high resolution (up to date) map created with drone overfly in the front.

Geolux’s communication integration protocol was extremely flexible and of great help in integrating target tracking and visualization technologies from multiple nations onto the real-time map.

Map generation using Sweden’s UAV’s camera to capture the demonstration site, was integrated into Geolux’s main view and was used as the background for the GIS visualization. This gave the Mission C2 Center the ability to easily display all the tracking information transmitted from each Nation’s tracking systems. The high-resolution Geo TIFF format gave the Mission C2 Center the perfect map to visualize the entire demonstration site and its outer perimeter. This enabled easy SAR participant geolocation using the real-time tracking data that was easily integrated into the lower resolution satellite map, which in turn provided the Mission C2 Center excellent SAR mission situational awareness.

Correspondingly, additional high-resolution map layers were added to visualize the internal infrastructure of each building used in the SAR mission. In addition to the top external views of the buildings, the Swedish generated internal maps (see Section 3.2.1) were used to produce detailed images of the interior walls and hallways in each building used for indoor navigation. As discussed in Section 3.1, the initial building internal point cloud maps were not georeferenced and required information from the external georeferenced information also provided by the Swedish team - see Section 3.2.1 for details. Finally, the outdoor and indoor generated map data was fused together to provide a detailed 3-D map of the SAR mission site (See Section 3.2). Using georeferenced data from 3 building corners, the indoor point-cloud image was automatically scaled and rotated to fit the building and could then be easily displayed over the building providing a 3D image that could be enlarged for better resolution – depending on the SAR mission phase and need (see Figure 4). In order to visualize each nation's technology, the demonstration visualization software assigned each nation's system with a predefined symbol to be shown on the range map. As shown in Figure 4, all tracking was shown in real time on the map in 2D (top view) and for the purpose of indoor visualization formatted data was sent to Swedish indoor visualization system running on the separate computer and tracking of all targets from any nations system was shown in the 3D view shown in Figure 5 below.

Figure 4: Mission C2 center visualization showing the tracking of the same targets using two different systems during the demo including the internal ground plane of the building shown for higher zoom level in the Mission C2 Center.

Figure 5: Actual picture of the Mission C2 Center visualization system highlighting the real-time simultaneous indoor/outdoor tracking in both a 2D top view on the map for general SA (right screen) and in 3D for better micro location awareness for indoor tracking.

3.0 COMPLEMENTARY PNT TECHNOLOGIES AND TECHNIQUES EMPLOYED DURING THE SAR MISSION:

The following sections describe the Complementary PNT Technologies and Techniques employed during the SAR Demonstration that was conducted on 16 Aug 2019. The details associated with the following 5 areas are presented in this section.

1) Outdoor / Indoor mapping
2) Personnel / vehicle tracking
3) Precision time transfer
4) GNSS Environment SA (Cel Phone Crowd Sourcing)
5) Red force tracking (Software Defined Radar

3.1 Outdoor / Indoor Mapping

Sweden demonstrated techniques for positioning of a UAV and ground units, and for collaborative positioning by improving the ground units' position estimates based on observations from the UAV. Sweden also provided mapping of the area and visualization of position data. Since the most relevant Swedish contributions were on lower TRL-levels, the remainder of this section describes algorithms and methods rather than final products.

3.1.1 Outdoor / Indoor Mapping for Position Visualization

The positions of units from the different countries were visualized by overlaying markers on maps and 3D models of the environment. The next subsections describe how these maps and models were generated.

Outdoors

Two representations of the outdoor environment were created: a textured 3D model and an orthographic photograph. Both were generated using photogrammetry, where a number of photos are used to compute the geometry and texture of the environment. The computation was performed using commercial software (Agisoft Metashape). The tool automatically finds points in the scene which are visible in several images and use these to compute the locations where the images were taken. When the camera locations and orientations are known, the 3D structure of the scene can be determined, and an orthographic photo can be generated.

In order to texture both horizontal and vertical surfaces in the scene, aerial photos were taken with the camera looking downwards and with it tilted 45 degrees relative to the ground. In total approximately 500 images, taken at two different altitudes, were used.

Since all images contain metadata about the approximate position and altitude of the UAV, the orientation and scale of the computed model and orthographic photo can be determined. To improve the precision, the automatic image matching was complemented by very accurate manually measured points from RTK GPS. Figure 6 shows the orthographic photo and a view of the 3D model.

Figure 6: Left: Orthographic photograph, Right: Textured 3D model.

Indoors

The interiors of some buildings in the area were mapped using a positioning and mapping system developed at FOI [1]. The system uses a ranging camera and an IMU and generates point cloud 3D models. Two-dimensional maps of each floor were created as vertical projections of these point clouds. Figure 7 shows a two-dimensional schematic of one floor in one of the buildings.

3.1.2 Visualization of Positions

The visualization tool for point clouds from indoor mapping was extended to be able to receive and visualize position data. Other participants in the group sent their position estimates to this tool, and the positions of their units were visualized in the 3D point clouds when they were located indoors.

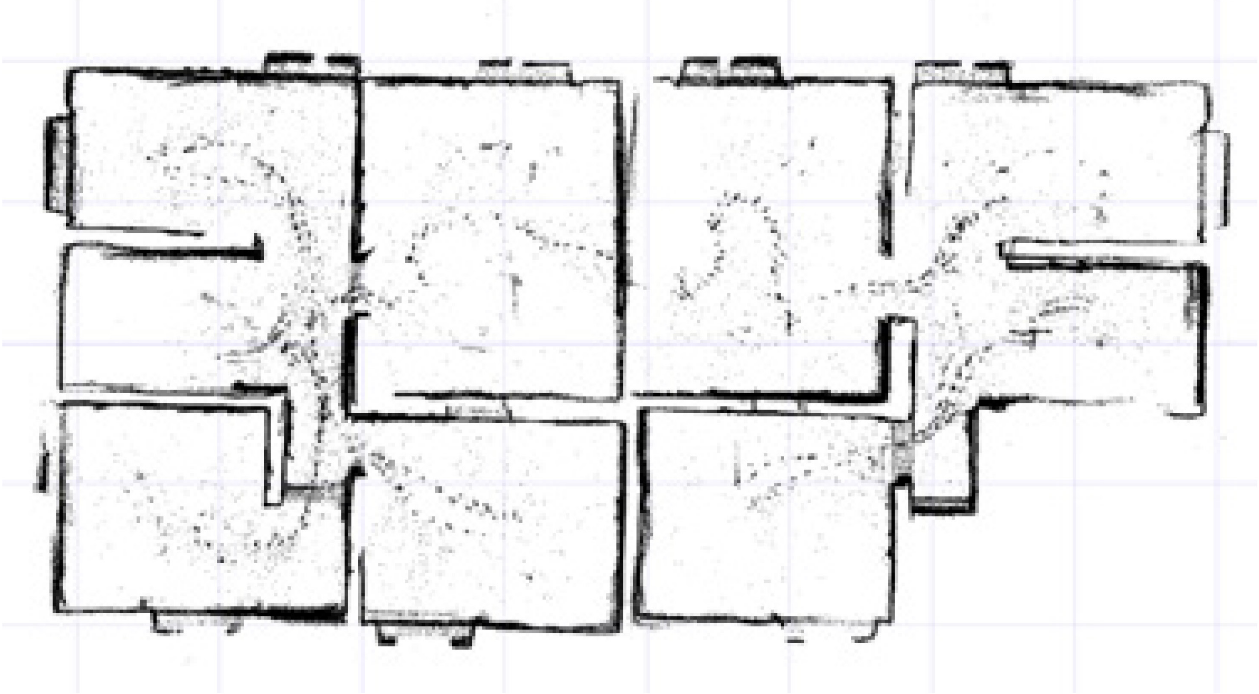


Figure 7: Two-dimensional schematic of one floor in one of the buildings.

3.1.3 UAV Positioning

A method for GNSS-free UAV positioning was demonstrated. In short, the method compares images from an on-board camera to a reference map of the operation area, and the position of the UAV is estimated by determining which part of the reference image is most similar to what the camera sees. In most environments, this type of map matching results in a number of different position hypotheses. This is handled by also estimating the velocity of the UAV from the camera images. A particle filter fuses the velocity estimates with the results from map matching and provides a final position estimate. This method is described in greater detail in [REF 2]. In the demonstration, we used the orthographic photo shown in Figure 6 as a reference map of the area.

3.1.4 Detection and Tracking of Moving Objects

Moving objects on the ground are detected and positioned based on images from the UAV. Estimated positions are sent to a central computation node, which also receives the ground units' own position estimates. Detections from the UAV, which can be associated to a known ground unit, are used to improve the ground unit's position estimate. Detections, which cannot be associated to any known unit, are assumed to be neutral or enemy units.

In each image, the detection method determines how all pixels have moved since the previous image. A moving object on the ground can be detected in this motion field since it causes a local deviation in the field. However, many false detections are generated, mostly because of parallax (objects which are closer to the camera, such as masts, roofs of buildings, etc. appear to move more than the ground). To reduce the number of false detections, the algorithm also requires that objects to be detected have a sufficiently different image intensity compared to their surroundings.

Using the estimated position and orientation of the UAV camera (from the UAV positioning method described above), the world coordinate of each detection is determined. Positioned detections are associated over time, forming tracks. To further suppress false detections, only tracks which move a sufficient distance from their starting position are used. (Under most circumstances, false detections only appear to move a few meters.)

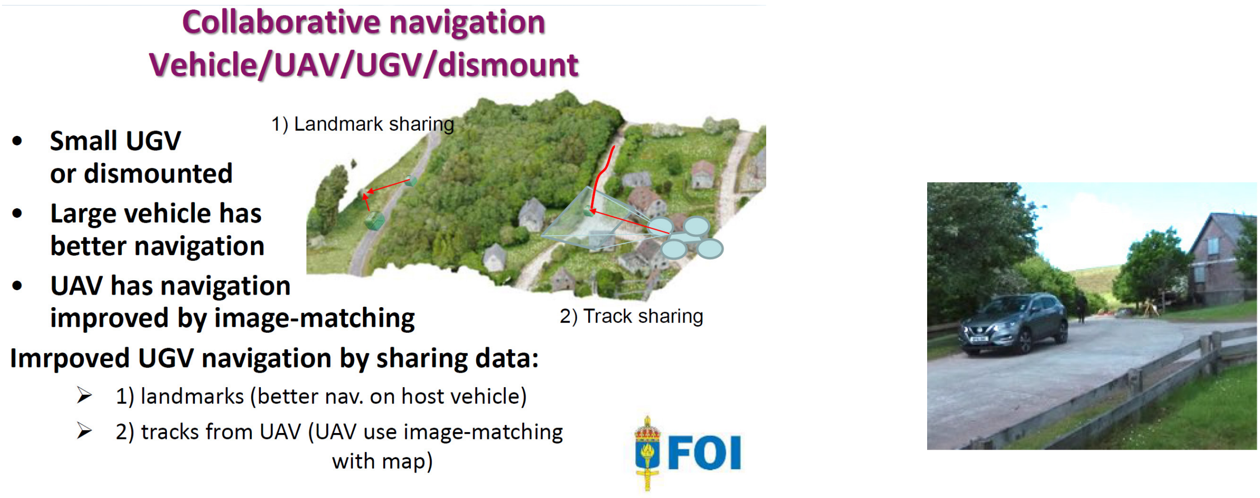
Figure 8 shows a part of the orthographic photograph of the demonstration area, with a red marker indicating the UAV position and blue lines indicating the estimated motion of two persons on the ground. The latest image from the UAV camera is shown in color, with the only detection marked by blue and red rings (the other person is not detected in this image).

Figure 8: Orthographic photograph of Demonstration Area. The UAV is marked with a red star and the motion of two persons on the ground are marked with blue lines. An image from the UAV is shown in color, with a detected person marked with concentric rings.

3.1.5 Collaborative Positioning

In the technology demonstration two aspects of collaborative navigation was presented – see Figure 9.

1) Collaboration through shared landmarks.
2) Collaboration through track-sharing.



Collaborative navigation
Vehicle/UAV/UGV/dismount

- Small UGV or dismounted
- Large vehicle has better navigation
- UAV has navigation improved by image-matching

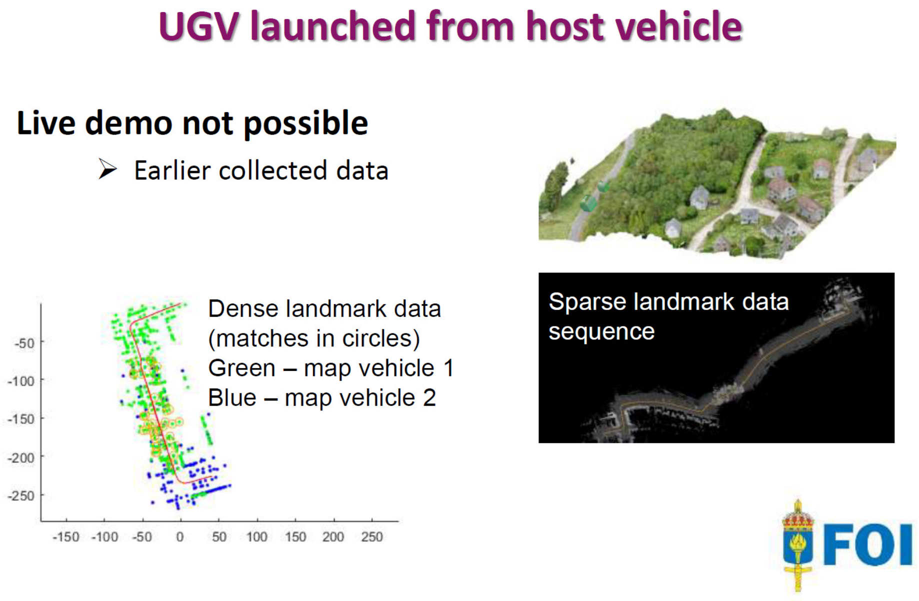
Imrpoved UGV navigation by sharing data:

- 1) landmarks (better nav. on host vehicle)
- 2) tracks from UAV (UAV use image-matching with map)

Figure 9: Collaborative navigation through track-sharing or landmark-sharing.

Both technologies were at too low TRL to be demonstrated live. For track sharing, data were collected at the site in a one-week measurement campaign during pre-trials in May 2019. Measurements were collected both for dismounts and vehicles (Figure 9 right picture). Collaboration by track sharing was only presented based on results from previous measurements [3].

Within the scenario the landmark sharing would allow the UGV launched from the host vehicle to get initial coordinates from the host vehicle by using shared landmarks along the approach (Figure 10). This part was only gamed during the final demo. The UGV together with the dismount then took the flank and when re-joining the group, it is tracked by the supporting UAV giving improved blue force tracking (Figure 11).



UGV launched from host vehicle

Live demo not possible

- Earlier collected data

Dense landmark data (matches in circles)
Green – map vehicle 1
Blue – map vehicle 2

Sparse landmark data sequence

Figure 10: Collaboration through landmark sharing.

Figure 11: Navigation supported by track-sharing from UAV. Data collected during the pre-trials, where red dots represent dead-reckoning by a foot-mounted system without support. The blue circles is the result after fusion with tracking data from the UAV (orthophoto background © Google & Bluesky).

3.1.6 Technology Background and Description for Collaboration by Track or Landmark Sharing

Both instances of collaboration above can be represented in Factor Graph form where the implementation GTSAM have been used [4]. Using a Factor Graph (which is discussed in detail in the "*PNT Fusion Algorithms*" papers), the relations from time-to-time can be represented statistically (in essence giving a smoothing filter representation). In Figure 12, the result for a simulated synthetic scenario of two vehicles starting with good position accuracy and the Factor Graph is used to represent the increasing uncertainty during dead reckoning along the full trajectory. The Factor Graph is then complemented with supporting information such as measurements on common landmarks (Figure 13), or measurements between the vehicles (Figure 14).

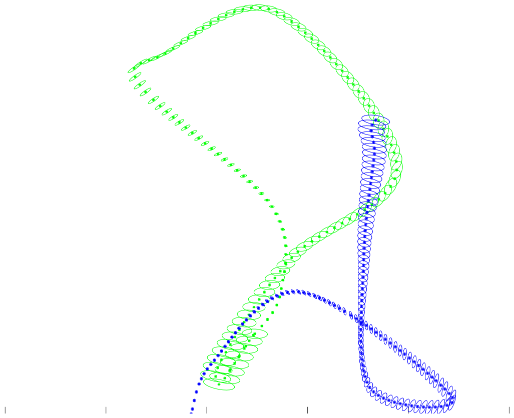


Figure 12: Illustration of increasing uncertainty in a simulated synthetic scenario with two vehicles where a factor graph represents the uncertainty between individual poses. The uncertainty in positions for the unaided dead reckoning Factor Graphs is illustrated by ellipses.

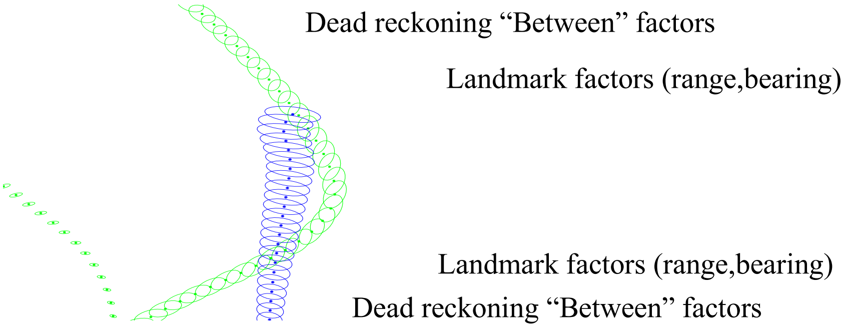


Figure 13: Example introducing supporting information through common landmarks. The motion between measurements on the landmark is captured by "Between" factors illustrated by the wavy lines and the measured range and bearing to the landmark is illustrated by arrows.

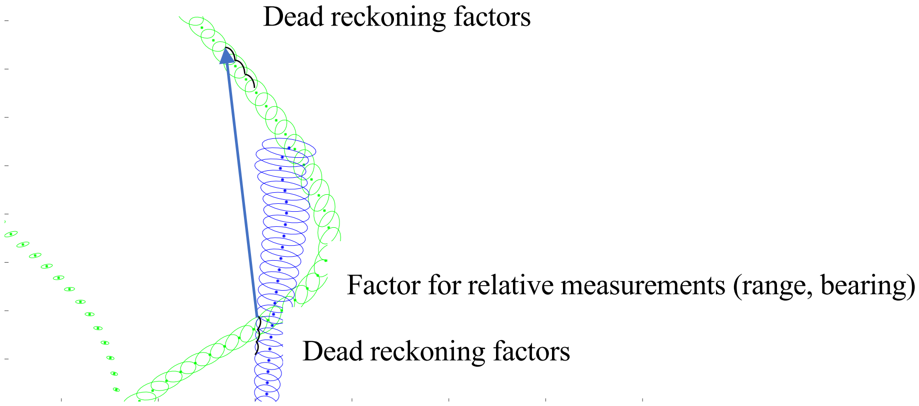


Figure 14: Example introducing information by a measurement between the vehicles. The motion between measurements on the second vehicle is captured by "Between" factors illustrated by the wavy lines and the relative measurement between the vehicles is illustrated by an arrow.

Ideally the full Factor Graphs would be communicated, but this is not always possible due to bandwidth limitations to communicate the full Factor Graph. Sometimes it is not even possible to access the UAV model of the correlation of dead-reckoning errors over time. Since the navigation errors evolve slowly over time, un-modeled correlation will introduce bias. For the demonstration a more robust method for fusion was used. At each time instance, when a report was available from the UAV, the GTSAM result for the ground unit was fused with the UAV track using a method that remains consistent also for unknown correlations (Inverse Covariance intersection ICI [5]). The trade-off in compensating for an unknown bias by this method is to accept a larger uncertainty in the result. The final result is illustrated in Figure 15.

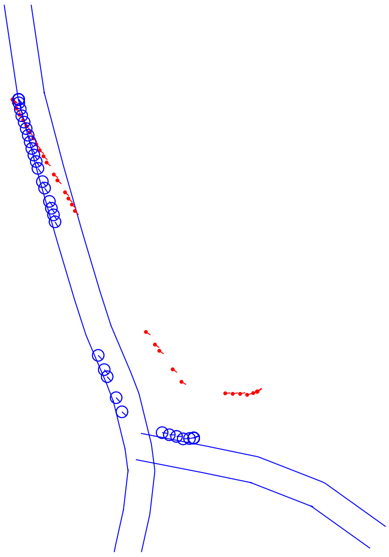
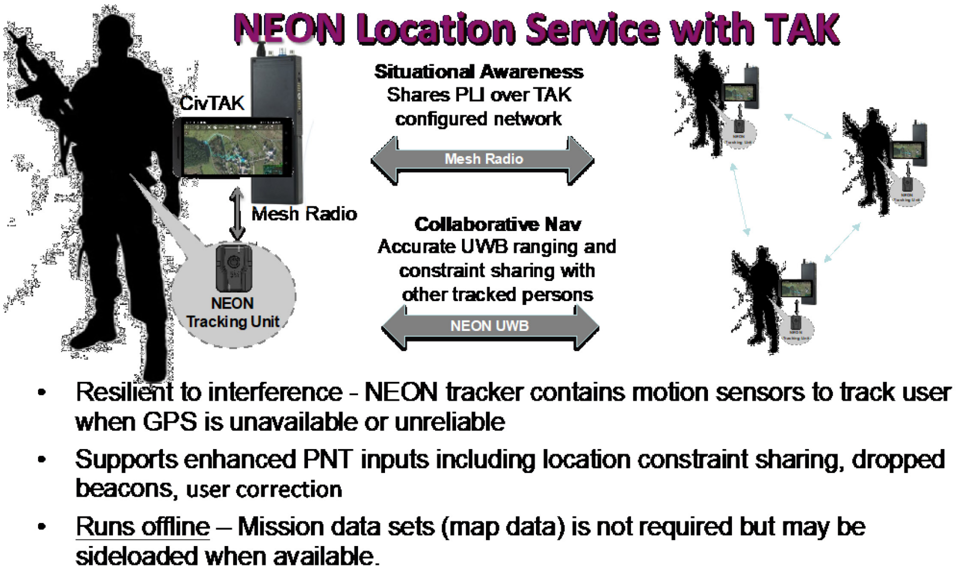


Figure 15: Result of fusion between track data from UAV using ICI (ICI blue circles) compared to pure dead-reckoning (red dots dead-reckoning). The motion is along the right side of the road crossing over to the left side in front of a house at the intersection.

3.2 Indoor / Outdoor Personnel Tracking

One of the most challenging aspects of providing location services is the ability to provide a seamless experience for a user with minimal or no user interaction as they move between operating environments (outdoors mounted or dismounted, with GNSS or without GNSS, indoors, underground or with GNSS interference). The TRX NEON dismount GPS-Denied system provides an assured location service that facilitates delivery of reliable, real-time 3D location based on advanced sensor fusion, ranging, and dynamic mapping algorithms. The location service uses body worn sensors, RF ranging, and optional map data to enable users to accurately track their location when GNSS is not available. The NEON ‘Tracking Unit’, Figure 16, is low size, weight, power (SWAP) and cost device that pairs with an End User Device that may run the CivTAK commercial interface. Assured PNT capabilities include:

- **Low-SWaP Inertial:** The Tracking Unit is a low-SWaP device that estimates dismount user motion direction and path using commercial grade MEMS inertial sensors.
- **Collaborative Ranging:** The tracker contains an ultra-wideband (UWB) ranging capability. The UWB ranging provides centimetre level relative position accuracy and supports location sharing between NEON equipped persons for collaborative navigation. The UWB ad-hoc network also supports sharing of user map ‘check-ins’, as well as ‘dropping’ of UWB reference beacons to provide automated location corrections to team members.
- **GNSS Integrity:** Knowledge of the user’s motion is used to enable the location service to determine the reliability of GNSS, which can be degraded due to multipath in urban areas or due to other interference sources, and to reject use of unreliable locations.
- **Collaborative Mapping:** Map data, including 3D building models, terrain, and collaboratively learned map information from prior visits to a site may be used (where available) to improve accuracy of position estimates when operating in GNSS denied environments. (The map data may be held centrally on a server and shared with all NEON users or cached locally each end user’s Android device when the NEON server is not accessible.)



- Resilient to interference - NEON tracker contains motion sensors to track user when GPS is unavailable or unreliable
- Supports enhanced PNT inputs including location constraint sharing, dropped beacons, user correction
- Runs offline – Mission data sets (map data) is not required but may be sideloaded when available.

Figure 16: TRX NEON Location Service Integrated with TAK and Mesh Radios.

The location service has a modular architecture and has been designed to facilitate integration with 3rd party systems. NEON has published Android application interfaces (APIs) providing the 3D location solution (e.g., to CivTAK, the Android user interface) and enabling extension of its collaborative navigation capability by taking in ranging or other position constraints from partner systems (e.g., ranging to 3rd party anchors, ground vehicles, UAVs). The integration with CivTAK enables sharing of location data of any configured TAK network. TRX is also developing hardware reference designs that support embedding of the NEON solution in 3rd party radios or other position, navigation and timing (PNT) devices.

3.2.1 Technology Demonstration Scenario Description

Figure 17 provides an overview and personnel track data collected during the demonstration. In the demonstration, three persons (two Recovery personnel and the hostage) were equipped with TRX NEON trackers, CivTAK end user devices, and mesh radios. The TRX NEON Commercial Command software (which runs on a PC) was used to show the location of all users including a 3D view of the building in which the Recovery occurred, complementing the CivTAK Android User Interface. A mesh radio was placed at NEON Command and another radio was placed near the intersection Figure 18) to ensure continuous connectivity of all tracked personnel through the Tactical Assault Kit (TAK) network to NEON Command throughout the scenario. The NEON location service provided each tracked person's location to CivTAK. The location was then sent over the TAK radio network to NEON Command. From NEON Command locations were shared over the command centre Wi-Fi network to the NATO Command Display. GPS was made unavailable throughout the village due to induced GNSS interference.

Initialization and Collaborative Navigation: Multiple test runs were executed for the Recovery scenario including some where the user's began operations where GNSS was initially available (and entered the village where GNSS was denied to interference) and others where operations began in the village GNSS denied environment. Figure 18 shows a replay of the Recovery scenario from NEON's 3D Command visualizer.

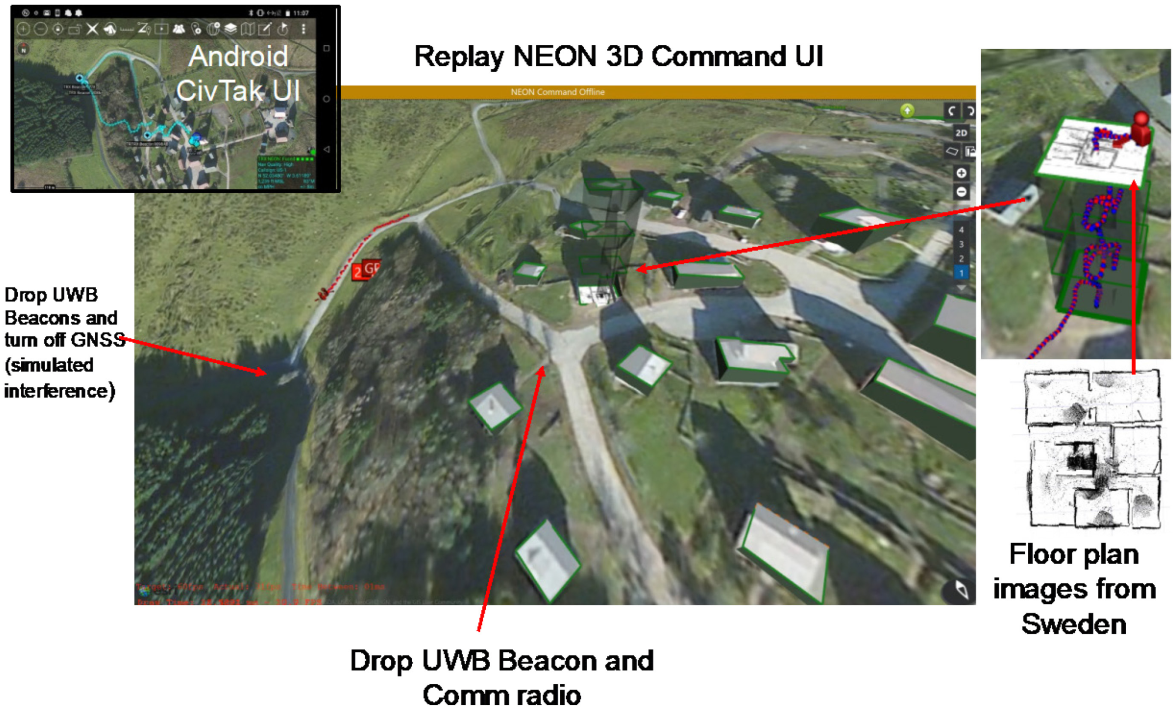


Figure 17: TRX NEON Command Replay of Demonstration Scenario.

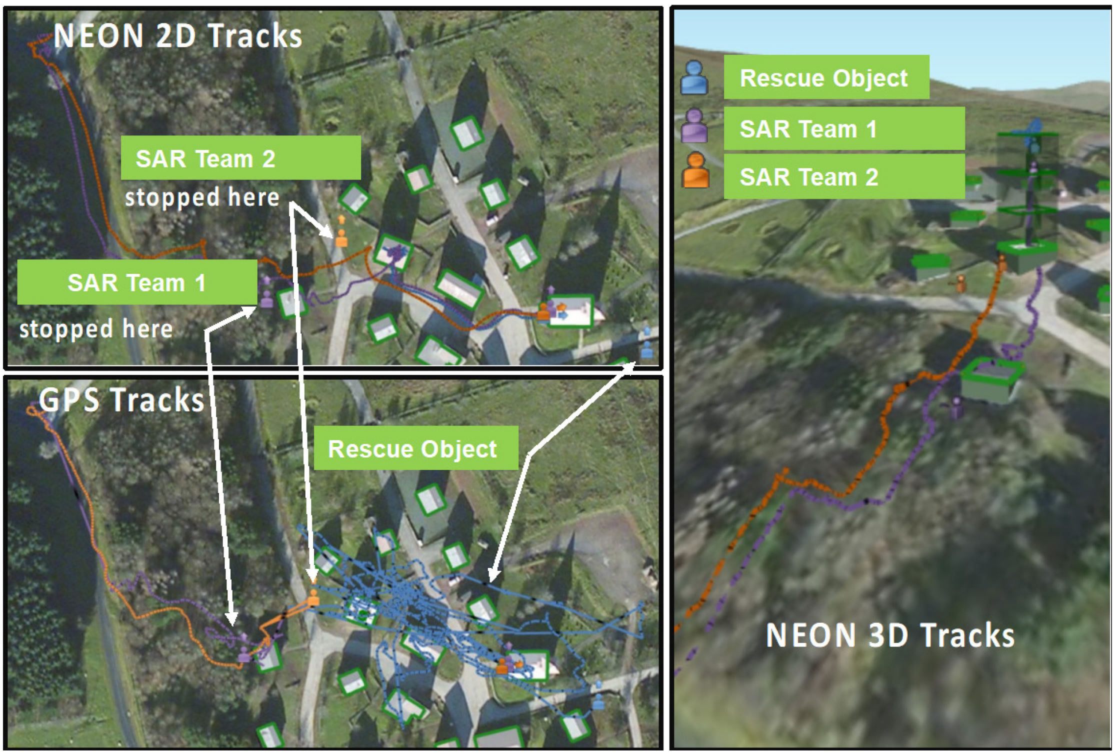


Figure 18: Scenario showing Initial Operation with GPS and Successful Continued Operation after GPS is Denied Due to Interference.

All users acquired their initial positions either with GPS or, for runs where GPS was not even initially available, using “map check-ins” (i.e., identifying their position by manually selecting their position on the map shown on the CivTAK user interface). For the cases where GPS was denied outside, beacons were dropped at the scenario start point (Figure 17, left) to simulate collaborative corrections from the team’s vehicle which would have higher quality, anti-jam sensors. The Recovery team lead’s NEON location service was configured to share location over the UWB ad-hoc network to improve the relative location between all team members during the mission. During the mission, a beacon was “dropped” near the rendezvous point before entry into Building 20 for the hostage Recovery in order to provide automated corrections during the Recovery to further improve location accuracy over the period of extended operations in the denied environment.

Situational Awareness: Given the offline configuration (i.e., lack of external internet or server access), terrain and base map data was cached in advance for NEON Command and CivTAK interfaces. The recovery object was located in the centre building (Building 20). 3D maps of that building were obtained by FOI (Sweden) based on a pre-mission survey. The extracted floor plan views along with the NEON tracked team’s locations were able to be viewed in the NEON Command and CivTAK visualizers for improved situational awareness. During the Recovery, the object and search team locations were able to be viewed in 3D as they searched the building (Figure 17, right hand side.)

3.2.2 Results and Analysis

The NATO test demonstrated the capability of NEON location service to provide subjectively accurate GPS-denied 3D locations meeting the use case requirements for delivering assured position operating in and out of environments with GNSS interference and supporting location and tracking of users in and out of buildings to the correct floor level. Collaborative navigation was demonstrated through UWB ranging between NEON equipped personnel and mounted vehicles/’dropped’ NEON beacons. The ability to view team 3D locations in and out of GPS coverage improved situational awareness during the Recovery mission and improved operational efficiency in executing the Recovery. Map data from NATO partners was integrated, demonstrating the benefit and feasibility of sharing geospatial data.

Successful collaborations:

- The NEON system was designed to be easy to integrate with 3rd party systems through published APIs. Using this API, TRX implemented a CivTAK plug-in. In the test this enabled location display on the CivTAK Android interface and location sharing over the TAK network.
- For the NATO test, TRX implemented capability to share locations through the TAK Network to NEON Command and then to share those locations using Geolux’s UDP protocol to the NATO Command Display run by Geolux (Croatia).
- The floor plans provided by FOI (Sweden) were able to be pulled into the NEON Command building models for each surveyed building before the final demonstration. A representative floor plan was added to the CivTAK 2D interface for each surveyed building as well. The floor plan data enabled improved situational awareness in Building 20. While not used in this test, the floor plan information would enable user corrections or beacon placement indoors to enhance location accuracy during a longer mission.
- Using Geolux’s UDP protocol TRX was able to share location to the FOI system mapping system and provide location in their 3D mapped building.

Future collaborations: Ideally in future test events, a NATO protocol would be established to facilitate collaborative sharing of location constraints and map data between teams.

- Aselsan (Turkey) also set up UWB beacons in the building providing overlook but the UWB protocols were different than those used in NEON so the NEON equipped personnel were not able to obtain corrections from the Aselsan beacons.

- FOI (Sweden) provided location corrections from unmanned air and ground vehicles to their tracked personnel. Establishing a NATO protocol for sharing such location information to other systems would facilitate collaboration.
- The NEON building model and the FOI building model did not have the same reference coordinates. Sharing of building data reference coordinates is important for visualization in 3rd party interfaces.

3.2.3 Summary and Benefits

TRX NEON provides a low SWaP Tracking Unit and a location service that facilitates delivery of reliable, real-time 3D location:

- **Sensor fusion -** provides estimation of relative user motion and posture based on body-worn sensors from both the NEON Tracking Unit and the Android device/Smartphone.
- **Dynamic feature detection and mapping** – improves tracking accuracy through geo-referenced 3D feature map including a priori map data as well as learned RF and structural features.
- **Collaborative navigation** – embedded UWB radios in the Tracking Unit enable collaborative navigation and relative location constraints that do not diminish over time.

NEON was able to extend CivTAK’s outdoor blue force tracking capability to include GPS-denied environments. Integrated via a NEON Plug-In for CivTAK, NEON users are seamlessly tracked inside buildings and in areas with GPS interference, gaining the benefit of dramatically improved situational awareness. Through the CivTAK UI, NEON users can access initialization indicators, manual check-in, and UWB configuration capabilities that allow for 3D tracking inside structures showing tracking details including stairways.

NEON incorporated Ultra-Wideband (UWB) technology that provided accurate ranging to enhance tracking accuracy. The NEON UWB Tracking Units support user-to-user sharing of location data, providing valuable location constraints between team members. Tracking Units can also act as UWB beacons that can be placed for a known event/activity or can be dropped ad-hoc at an incident; in either case, providing a highly accurate location constraint for all users in the group.

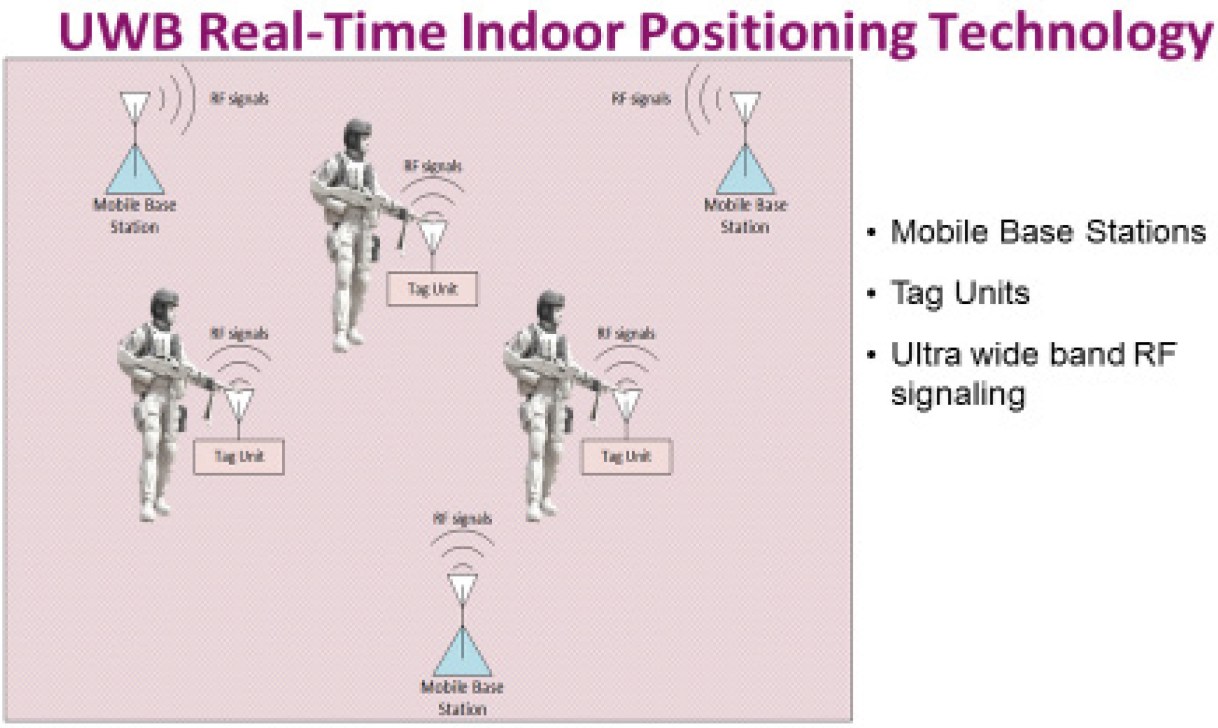
NEON detects GNSS interference and provides an indication of disruption events via CivTAK or through the NEON API. The approach includes integrity monitoring using inertial sensor fusion to deliver assurance and can, optionally, be integrated with 3rd party GNSS Assurance software.

3.3 Indoor Personnel Tracking (Turkey)

3.3.1 Technology Background and Description

One of the most crucial needs in military operations is to provide soldiers with an accurate and reliable positioning information for their safety and for the success of operations. While GNSS based outdoor positioning is greatly advanced, indoor positioning is still an open issue due to the unavailability/degradation of GNSS and the complexity of indoor environments. One of the solutions for indoor positioning is Ultra WideBand (UWB) technology. Indoor positioning with UWB (Figure 19 depicts the UWB system) has some significant advantages such as:

- Decimeter-level positioning accuracy (better than 30 cm), dependent upon obstructions and anchor node density/geometry,
- Large bandwidth,
- Low transmit power,
- Immunity to multipath fading.



UWB Real-Time Indoor Positioning Technology

- Mobile Base Stations
- Tag Units
- Ultra wide band RF signaling

Figure 19: ASELSAN's UWB Indoor Positioning Technology.

The ASELSAN team's UWB real-time indoor positioning technology and developed a prototype system. As shown in Figure 19, The prototype system consists of mobile base stations and tag units. The prototype system operates at 4.5 GHz and uses a Time of Flight (ToF) positioning algorithm. The use of algorithm requires at least three base stations with surveyed locations as accurately as possible. The positions of tag units are calculated by using ToF values and a trilateration method.

3.3.2 Technology Demonstration Scenario Description

As mentioned throughout this paper, the technology demonstration scenario was designed as a search and Recovery operation. In the scenario, ASELSAN UWB team served as a "Pre-installed Overwatch Team" together with Roke Team. In the demonstration, Building 16 – the observation building – was surrounded by 4 mobile ASELSAN UWB base stations and the surveyed position information of base stations were provided by FOI.

During the mission, Overwatch Team took its starting position at the rendezvous point near the observation building. After meeting with the Recovery Team (TRX from the USA), the Overwatch team started to move to reach the observation building using the Visual Odometry System of Roke. Once the observation team entered the UWB base station area which was surrounding Building 16, ASELSAN's UWB positioning system became activated, and the tracking of 2 ASELSAN members equipped with tag units started to share their information with the Mission Command Center (MCC) over the Wi-Fi network and their positional data was displayed in real-time on the NATO Command Display. After checking the suitability of the field for the operation, the observation team gave the signal in order to start the Recovery mission for the hostage in Building 20.

Figure 20: Technology Demonstration.

3.3.3 Results and Analysis:

In this cooperative technology demonstration, ASELSAN UWB Indoor Positioning System fulfilled its own task successfully. Centimeter-level indoor positioning accuracies were obtained despite the obstacles such as the thick concrete walls of Building 16 and objects in and around the site. It was seen that the performance of the system heavily depends on locating the base stations on accurately surveyed positions. Thanks to FOI's pre-mission survey, each UWB base station was placed at a very accurate georeferenced position. Thus, such a centimeter-level positioning accuracy for tag units could be obtained.

3.4 Seamless Outdoor / Indoor Personnel Navigation and Tracking

3.4.1 Technology Background and Description: The Roke Exploration Navigation System

The Roke Exploration Navigation System (RENS) provides accurate positioning and orientation information, seamlessly, in environments where access to satellite-based signals such as GPS or GNSS is intermittent or not available. RENS exploits and extends research from the field of Inertial Visual Navigation, Computer Vision and Simultaneous Localisation and Mapping (SLAM) in support of our design philosophy that insists alternative sources of PNT data are needed to improve deployment/application use and reduce costs. The data fusion of pose information generated from two very different sensor modalities, inertial and visual, is a key aspect of the technology development.

3.4.1.1 Technology

RENS is based on a Visual Odometry (VO) system using a state-of-the-art, novel, parallel semi-dense feature-based tracker. It determines the rate of change in position and orientation between current and past poses and uses IVNS (Inertial Visual Navigation Solution) fusing with integrated inertial measurements from an IMU (Inertial Measurement Unit) to correct VO accumulated error. RENS requires no deployed infrastructure (active or passive) with no need for Radio Frequency beacons or pre-surveying of sites to be carried out. This greatly improves operational stealth and reduces supply and support costs.

3.4.1.2 Methodology

Two key software components of RENS, developed by Roke, are the sensor processing (PinPoint) and data fusion (IVNS). They are designed to be distributed or centralised due to the lightweight middleware used, and can be cross compiled on both Intel and ARM processors for Linux and MS Windows operating systems

- PinPoint is a sensor processing head service for downstream clients. It extracts information from the camera, manages the IMU data, and maintains hardware sensor time synchronization, to provide logging and network streaming data capabilities as a service. The service can log or stream time synchronized IMU, images and feature points. PinPoint is sensor hardware agnostic, allowing tailoring to user requirements by selecting appropriate COTS hardware. Using an interface standard means different sensor hardware can be used to form different solutions and ensures that there are no third-party dependencies in downstream software processing components.
- IVNS fuses the inertial and visual information to provide accurate position and pose. It consumes data from PinPoint and provides 6DOF position and orientation information with uncertainty error as a service. There are many algorithms and engineering functions within IVNS. Some of these include: IMU calibration, camera calibration, point correspondence estimation, monocular observation depth estimation, 3D pose estimation solvers, visual odometry estimation, Bayesian information fusion, Zero Velocity Update (ZUPT), information boosting, visualization, analytics and networking.

The high-level architecture of PinPoint and IVNS services, as Input-Process-Output System models, are shown in Figure 21 and Figure 22 respectively.

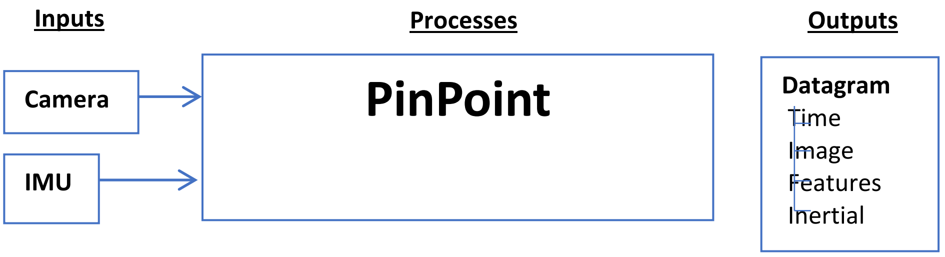


Figure 21: Input Process Output Model for PinPoint.

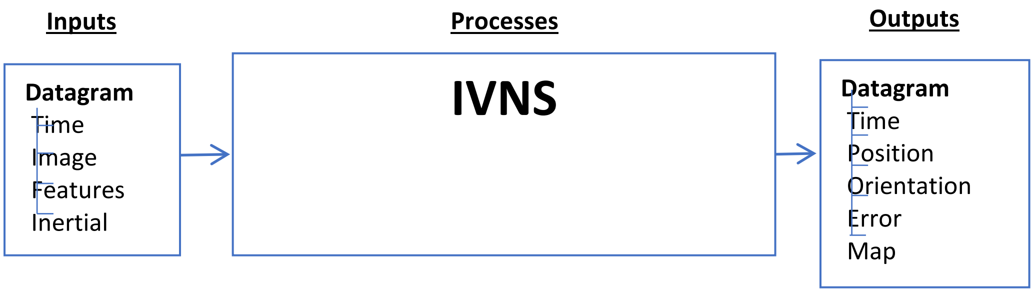


Figure 22: Input Process Output Model for IVNS.

3.4.2 Application

Within the NATO community there is a requirement to develop a capability that enables personnel to utilise alternative sources of PNT data effectively for navigational systems (or other systems for Coordinated Universal Time (UTC) or positional data) to either supplement or replace a degraded or denied GNSS source. In this application, deployed forces are provided with a RENS module (Figure 23) which displays information to the soldier through interfaces in current hand-held weapons and helmets and plug-in to an existing chest worn mobile phone Tactical Assault Kits (TAK) or Virtual Reality Headset.

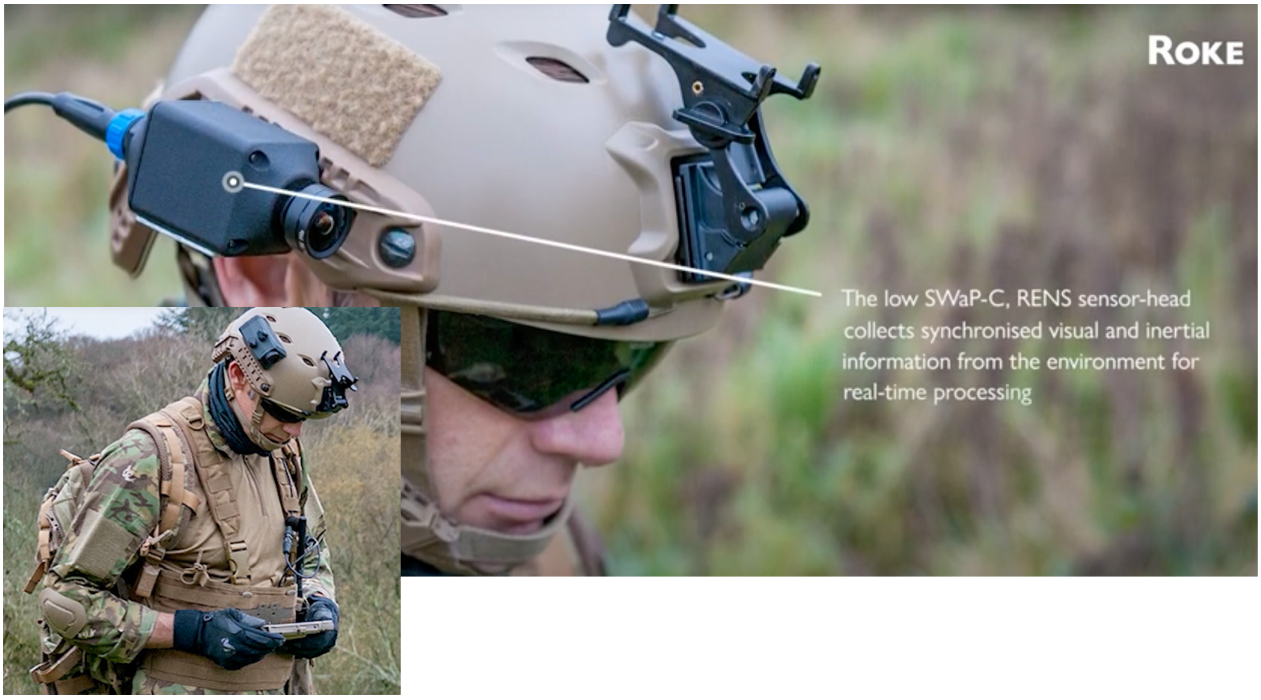


Figure 23: Dismounted soldier with an example RENS Module helmet mounted and position information displayed on a mobile phone.

3.4.3 Results

The RENS prototype has been demonstrated in semi-representative environments, whilst also supporting laboratory experiments for continual system analysis and algorithm enhancement. For demonstration and testing purposes, RENS used WiFi to allow communication with a central command and control and a mobile phone, for real-time globally referenced positioning and orientation on a map.

Figure 24 depicts a result of a single trajectory (red line) of a person walking in and between buildings, performing a three-building search in the test area.

3.4.4 Summary

RENS is a fully functional prototype of a next generation real-time, independent, navigation capability for multiple use-cases both mounted and dismounted personnel. RENS fuses data from a standard monocular camera and low-cost IMU to provide position and orientation information without reliance on GPS/GNSS, prior Information, beacons, active sensors, or surveyed infrastructure. It therefore functions in GPS-denied and other contested or jammed environments; where other sensors would fail, RENS therefore enables essential situational awareness.

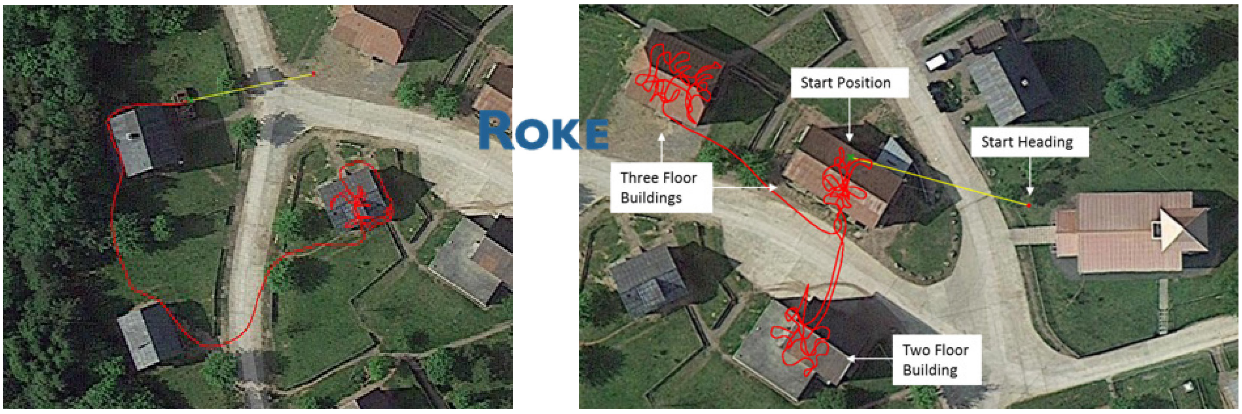


Figure 24: Satellite images of test area with a person's RENS measured trajectory (red line).

3.5 Precision Time Transfer (USA)

3.5.1 Technology Background and Description

Today, Global navigation satellite system (GNSS) provides a convenient, inexpensive, and ubiquitous method of delivering time synchronization to Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance (C4ISR) systems installed on mounted (ground/airborne) and dismounted platforms. Precise time distribution enables many tactical advantages on the battlefield including, but not limited to, situational awareness and high bandwidth communications. Unfortunately, the weak signals from satellites make GNSS vulnerable to outages which can expose the user to unnecessary risk when their systems fail due its absence. Maintaining synchronization independently from GNSS is critical to preserve the functionality of such systems. Alternative time transfer mechanism allows systems within an Area of Regard (AOR) to be synchronized even in GNSS-challenged environments.

Time transfer technology is a mature technology that transfers precise time from a reference clock to another clock over a wired or wireless network. Similar time transfer methods include Network Time Protocol (NTP) and Precise Time Protocol (PTP). To achieve accurate synchronization, path delay and time offset between the two clocks must be considered and corrected. Two-way time transfer (TWTT) offers an automatic removal of the path delay, as the two peers both transmit, and also receive each other's messages allowing the difference between the clocks to be determined and the path delay removed. Current implementations of TWTT include a commercial geosynchronous satellite network to synchronize time among national laboratories in the world. Proven TWTT technology can be leveraged for its implementation on the tactical network. The use of communication bandwidth on the network should be negligible since time information is transmitted on a need basis to correct the drift of a holdover clock and does not necessarily need to be sent continuously.

3.5.2 Technology Demonstration Scenario Description

The scenario is shown in Figure 25 to demonstrate a wireless time transfer method to the Croatian security Software Defined Radar (SDR) systems which require time synchronization of the radars connected to the network.

The radio system transfers time among the radios by using Precision Time Protocol (PTP) with <1 microsecond accuracy. The radios provide multi-hop synchronization and output synchronization signals (timestamp and 1 pulse-per-second) to timing users. For this demonstration, the radars receive timing signals from the radios so that they may be synchronized in GPS/GNSS-degraded/denied environments. Figure 26 shows the test set-up of the radar connected to the time transfer radio. A PC is employed to control and provide the interface for data transfer between the radar and the radio.

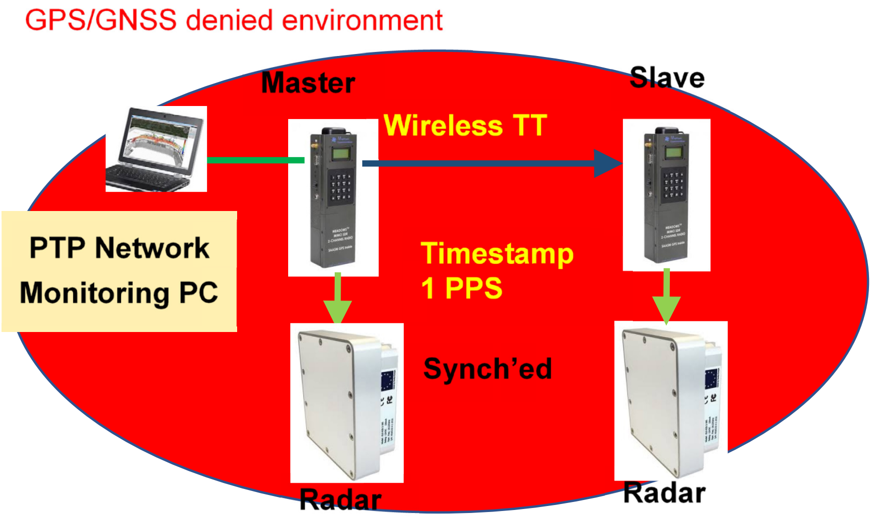


Figure 25: Wireless synchronization of Croatian security radars.

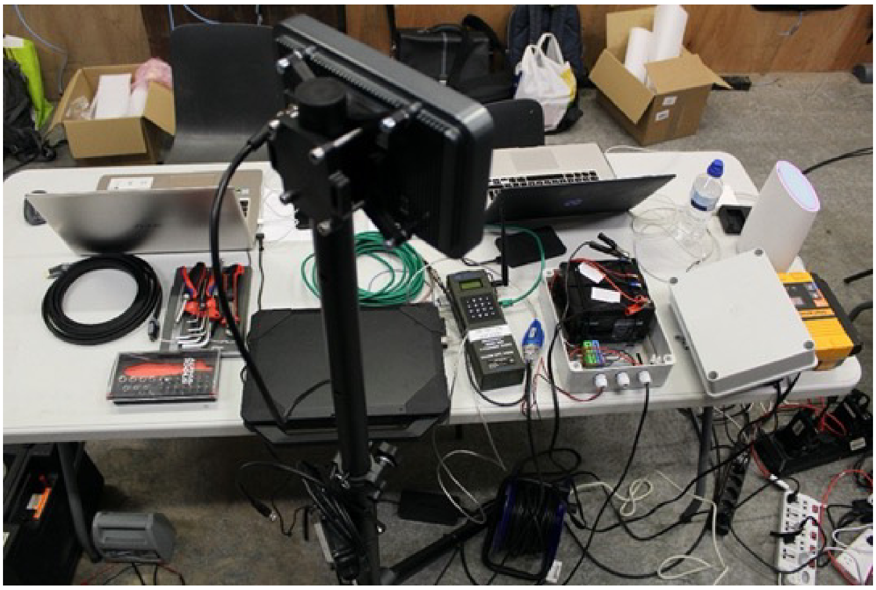


Figure 26: Time transfer demonstration set-up testing.

3.5.3 Results and Analysis

The PPS sync between the radios was measured using a standard oscilloscope. The system consistently maintained synchronization to within 100 ns. The radios transferred their time to the security radar systems via PPS and a NMEA timestamp message to synchronize the radars. With no time synchronization, the combined radar image could not correlate the same target from two different radar systems and showed multiple detects for one target (one-detect per radar) as seen in Figure 27. With time synced, the radar correlate hits from multiple systems and show a single target on the map.

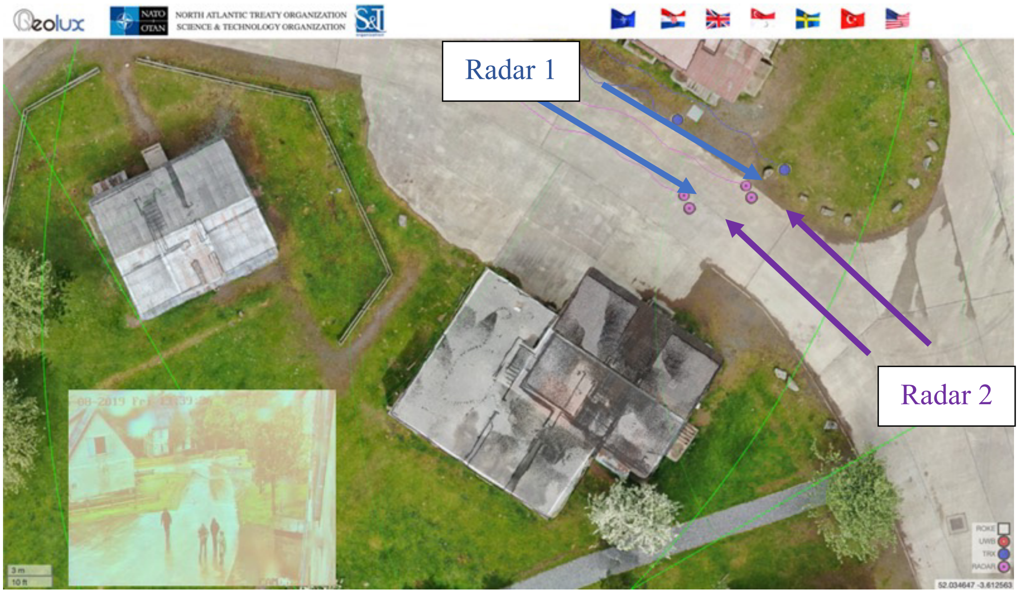


Figure 27: Uncorrelated radar images due to no time synchronization.

3.6 GNSS Environment SA

3.6.1 Technology Background and Description: GNSS Monitoring System

GNSS is critical for many different operations. The lack of GNSS situation awareness would have adverse impact on the efficiency and effectiveness of these operations. One solution is to provide an effective means of GNSS signal integrity monitoring through smart devices, crowd sourcing and distributed nodes.

A GNSS Monitoring System adopted a crowd-sourcing approach and leveraged Android based smart devices for the collection of GNSS information via its on-board GNSS chipset. Figure 28 shows the prototype architecture for the system. The application allows for the extraction of the GNSS carrier-to-noise (C/No) density ratio and location information. An averaging of the C/No for each GNSS constellation (GPS, GLONASS, BEIDOU and GALILEO) is computed on the smart devices and sent to a local repository. A client C2 was also developed to extract and display the location and C/No information on a map to provide situation awareness of the GNSS signal integrity within the area of operation (Figure 29). The quality of measurement used includes both the average C/No readings as well as the number of satellites in view for each constellation.

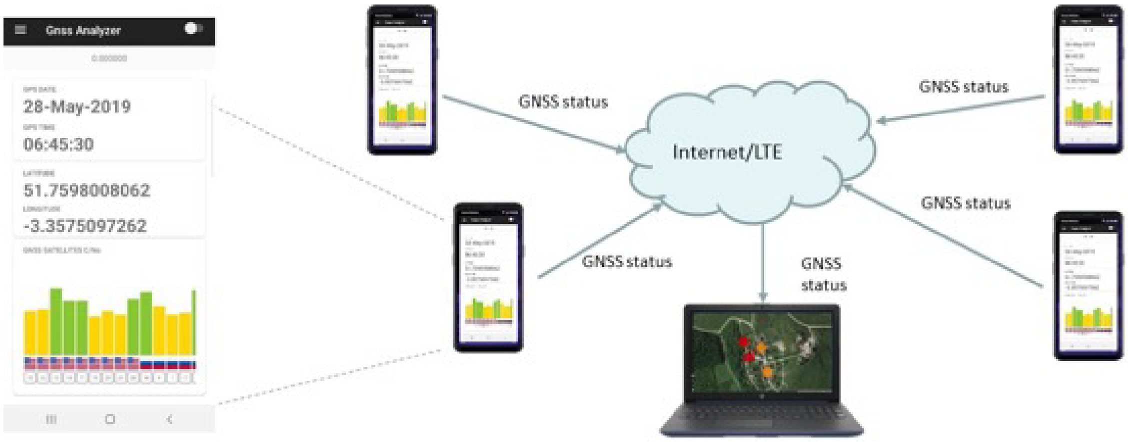

28-May-2019
06:45:30
51.7598008062
-3.3575097262

Figure 28: Architecture for GNSS Monitoring System

Figure 29: GNSS monitoring system C2 display.

3.6.2 Results and Analysis

The GNSS monitoring system was able to provide real-time situational awareness from a partially degraded environment to a fully denied one when the transmission power of the interferers increased in ~5dBm steps. The crowd-sourcing concept using smart devices to provide GNSS situation awareness (for ultra-low-power interferer) is feasible and its utility increases with more sensing nodes and mobile data coverage. The key takeaways from the trials are:

1) **Jamming effects in urban environment.** The effects of the jammer in an urban environment is less effective when compared to that of an open environment. This allows the obtainment of a location fix by GNSS by using obstacles, such as buildings, as RF shields. This could be incorporated as part of User's training, tactics and procedures to enhance resiliency in the presence of interferers when operating in an urban environment.
2) **Varying baseline for GNSS signal quality for a given environment.** The team observed that the measured GNSS signal quality varied depending on the deployment environment. The current methodology of using a fixed measurement threshold to determine the GNSS signal quality could be further refined to enhance system robustness. A possible alternative could be to perform pre-sensing of the GNSS environment for a given deployment site and to use the collect data to determine the thresholds.

Future development could incorporate a wider suite of GNSS measurement parameters including the raw data frames. The C2 client could be further enhanced to provide a richer set of visualisation features.

3.7 Outdoor "Red Force" Tracking

3.7.1 Technology Background and Description: Outdoor Software Defined Radar (SDR) Objects Tracking

Knowing the location and movement of the enemy's "Red Force" is of critical interest in any SAR mission. For the SET-229 Demonstration, Geolux developed a compact microwave SDR radar that was extremely easy to deploy and set-up in order to quickly detect all moving objects in the perimeter in front of the radar. Any object of interest (static and/or dynamic) could be easily located and tracked without a requirement for each object to emit any signal. The SDR radar itself, working as an active, very low 100 mW EIRP (Effective Radiated Power) FMCW (Frequency Modulated Continuous Wave) signal transmitter was able to detect all objects, moving or static, in a range of 150 m with a 90° field of view in horizontal plane. Target detection and location is accomplished by processing reflections from the SDR's microwave signal that returns from the target itself. The target doesn't require any active RF transmitter which is very important for the modern battlefield since transmitting targets are easily located with modern technologies. The SDR radar's distance location accuracy was in the range of ±0.5 m with a ±1° angular accuracy.

Radar detection and location of the targets is not dependent on the GNSS signal or jamming, so this method is a good alternative for location of objects in outdoor perimeters where GNSS location based on traditional satellite methods is not possible. The radar can track up to 32 targets simultaneously and are reported in the distance/angle format related to the position of the radar. If geolocation of the targets is required only, the geolocated position of the radar, usually in a fixed single location, is required and from this information all other geolocations of the targets can be calculated.

As shown in Figure 30, the SDR's architecture – with digital beam forming and no movable parts – allows the radar to be one of the smallest radar's in this class on market. With its small Size, Weight, and Power (SWAP) – dimension 210 x 130 x 30 mm and power consumption less than 10 W – it is ideal for battery power and tripod mounting.

The SDR was connected wirelessly (this was achieved with multiple wired and wireless interfaces enabling the device to operate from remote locations for longer time period with only a small battery pack and mounting structure required) to the Mission C2 Center and provided real-time red force tracking.

Figure 30: SDR ground surveillance radar, installation of the system for the demo.

3.7.2 Results and Analysis

During the NATO SET-229 real-time SAR demonstration, 3 radars (Figure 30) were located to monitor the perimeter of high interest during the SAR operation (Figure 31). Two radars were sharing one location looking in different directions to cover FOV of 180° and one radar was located on the location opposite the perimeter and covering exit path from the operation range (see Figure 30, Figure 31, and Figure 32).

In order for the SDRs to provide real-time geolocated target information, the radars were placed on previously 3D surveyed positions (courtesy of the Swedish team – see Section 3.2.1 for a discussion regarding landmark geolocation techniques). The SDR's internal magnetometers were the only additional sensors used in determining the centerline heading for each geolocated radar. All target tracking in the system was related to the location of the radar and transformed to the geolocation coordinates in the Mission C2 Center software.

The radars were connected to the Mission C2 Center using wireless communications – standard WiFi was used during this demonstration, but the system could have easily used any standard tactical radio network with support for a standard Ethernet connection or serial RS232 or RS485 communication channel.

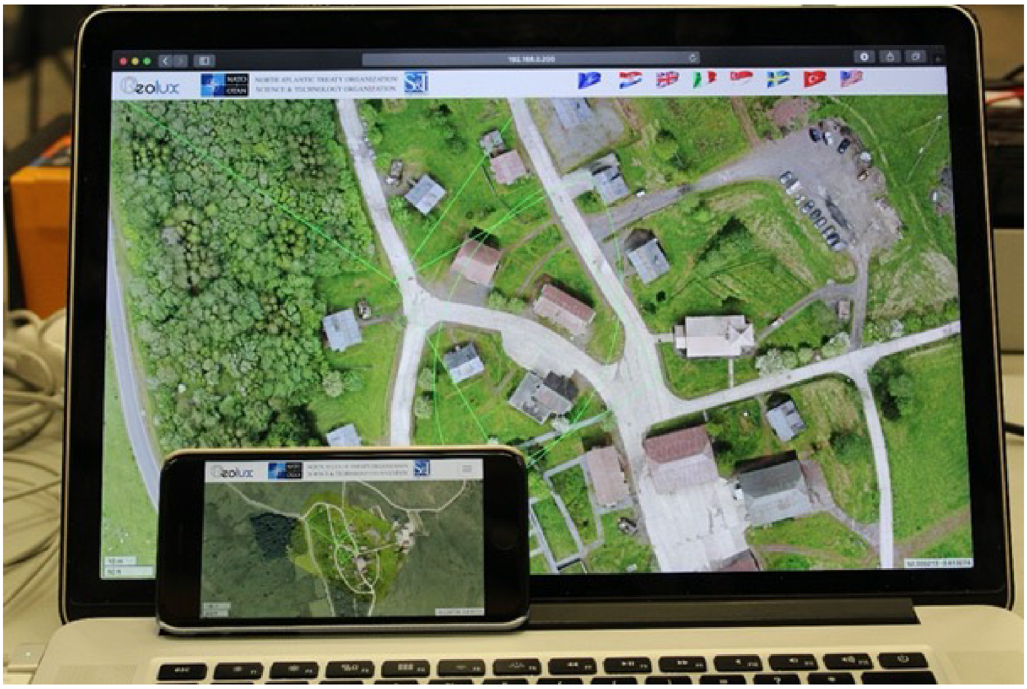


Figure 31: Demo range overview with radar locations and FOV (field of view) for each radar.

Figure 32: Range map with location of the radars and FOV for each radar.

During the demonstration, there were significant variations in the weather with several periods of heavy rain showers and changeable winds in both speed and direction. It is important to note that heavy rain showers usually increase radar reflection attenuation and introduce problems for ground surveillance radars.

However, when this situation occurred during the SAR demonstration (even with heavy rain shower), the SDR operated properly and without any significant performance degradation. In all cases, target (both friend (blue) and foe (red)) detection and tracking had high reliability, as expected for the distances monitored and the topology for the demonstration site. All blue and red targets were detected, and their locations were precise – without any GNSS signal availability. Also, in addition to all moving blue targets being detected and tracked, the radar tracks provided reasonable overlap compared to the other nation's tracking technologies (see Figure 33 where the blue circles represent the USA TRX tracking system and the yellow dots represent the radar tracks).

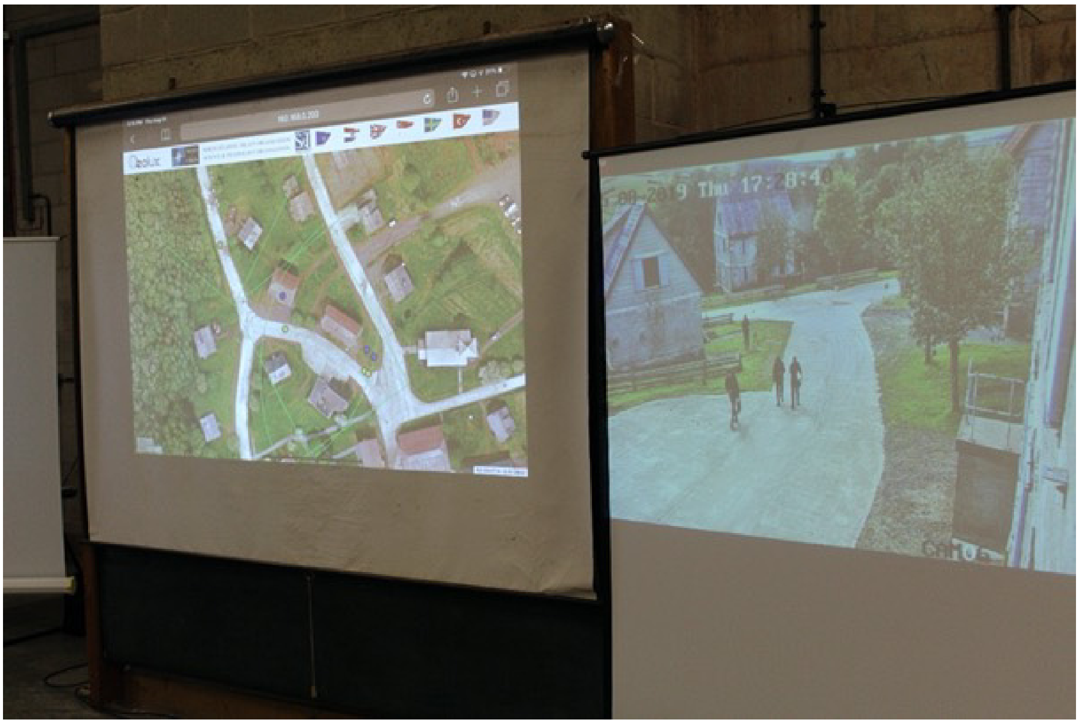


Figure 33: Real time view from the Mission C2 Center screens (left - range top view map, right – video image from camera in the range).

The realistic SAR demonstration highlighted the ground surveillance radar's ability to locate a target when precise GNSS is either not available or dependable. The outdoor tracking solution was not degraded over time. However, caution must be used in placing the ground surveillance radars, since their performance is highly dependent upon the terrain configuration and that it is impossible for the radar to detect and locate targets located behind obstacles. This highlights the importance that should be placed on an integrated system using disparate technologies to provide cooperative/collaborative solutions.

4.0 SUMMARY

The NATO Research Task Group, SET-229, on "Cooperative Navigation in GNSS Degraded / Denied Environments" was formed in 2015 to focus on PNT technologies, techniques, and methods to enhance NATO effectiveness in GNSS degraded/denied environments through the improved use of advanced, cooperative/collaborative PNT technologies and techniques. NATO and Partners for Peace experts from government, academia, industry, and the military spent 4 years to design, develop and demonstrate Cooperative Navigation technologies and techniques to enable effective PNT operations and PNT Situational Awareness (SA) in GNSS Degraded / Denied environments. As presented in this Final Report, the SET-229 RTG's 4-year effort culminated with a real-time SAR mission conducted in a GNSS degraded/denied environment. The RTG planned, organized, and demonstrated complementary PNT technologies in a realistic SAR operation. The demonstration involved PNT technologies from 7 countries. The SET-229 team demonstrated advanced Complementary PNT technologies and techniques allowing precision indoor/outdoor mapping, precision navigation, and personnel tracking (friend and foe) in hostile GNSS environments that might be present in a SAR operation in a hostile territory. This paper summarized the excellent work of the RTG, including a description of the products generated by the group, and provided an overview of new and emerging navigation sensor and system technologies that will impact future PNT operations worldwide.

5.0 REFERENCES

[1] [CHAMELEON] Joakim Rydell, Erika Bilock, Håkan Larsson, "*Navigate into Danger"*, Proceedings of IEEE/ION PLANS 2016, Savannah, GA, USA, 2016.

[2] [ION2019] J. Rydell, E. Bilock, M. Tulldahl, "*Computationally Efficient Vision-Based UAV Positioning*", Institute of Navigation International Technical Meeting (ION ITM), 2019.

[3] [TECH-REPORT] F. Näsström och et.al., "Intelligenta spaningsfunktioner 2016-2018 - Slutrapport," FOI-R--4648-SE, Linköping, 2018.

[4] [GTSAM 2012] F. Dellaert, "Factor graphs and GTSAM: A hands-on introduction," 2012.

[5] [Automatica 2017] B. Noack, J. Sijs, M. Reinhardt och U. D. Hanebeck, "Decentralized data fusion with inverse covariance intersection," Automatica, vol. 79, pp. 35-41, 2017.