Coordinated maritime missions of unmanned vehicles – network architecture and performance analysis

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***Abstract*—Multi-vehicle operations using various types of unmanned vehicles (UVs) can increase efficiency of marine data acquisition, reduce the crew risk and lower mission costs. These types of missions are very complex and often involve systems that are not interoperable. From an operational perspective however, some level of integration is necessary. Typically, a common network system architecture and Situation Awareness (SA) platform are required. The architecture allows operators to transfer data between vehicles and their operators, while the SA platform allows to monitor mission progress and react to changes.**

This paper presents a network system architecture used during an experiment realized in Spring 2016 in Norway. 8 departments from 5 institutions worked together to combine operation of 4 UVs (aerial, surface, underwater), a support vessel and on-shore team. The description is followed by a backbone network performance analysis. Several cases are presented, with focus on a transmission between manned vessel and Unmanned Surface Vehicle (USV), including direct connection, and data-relay mechanism via Unmanned Aerial Vehicle (UAV).

I. Introduction

Coordinated maritime missions of manned and unmanned vehicles (UVs) are very complex tasks and require intensive preparation. Work is needed in both hardware and software integration [1], [2]. Multivehicle operations often involve multiple partners, that use different systems, often not compatible with each other. However, from operational perspective, some level of integration is required in order to provide common Situation Awareness (SA) mechanism. Mechanism should allow operators to monitor mission progress and react to changes and adjust the way the actions are executed. In addition such system requires a common network architecture and a dedicated high level software.

The need of broadband communication on the sea is widely emphasised in the literature [3], [4], [5], [6]. For example in the Northern and Arctic Region suitable communication means are needed for reporting on the environment factors and pollution threats. A broadband radio with data rates of several Mbps is needed, for fisheries, oil and gas industry, the Coast Guard and research. One of the aspect that need to be investigated are additional ways to extend the communication coverage and range, including mobile multi-hop relay (MMR) [7] and repeaters [3]. Technologies present in the current literature tend to use 802.16 networks [3], [4], [5], [6], [8], where an optimum range between nodes is less then 5 km, and effective range is 5-30 km [6]. Scenarios and network architectures for maritime communication are also presented in [5], [6], [8].

This paper presents details on the network system architecture, and its backbone communication link performance, that was used during an experiment realized in Spring 2016 in Norway. The backbone communication link was created using a Maritime Broadband Radios (MBR) by Kongsberg [9] and compatible Radionor Communications [10] radio, used also in [11]. The motivation of the project was to explore possible ways of UVs cooperation, in order to reduce manned support vessels involvement in maritime operations [12].

More autonomous operations can increase efficiency of marine data acquisition, reduce the crew risk and lower mission costs. One of the key factors of coordinated operations of UVs is a reliable communication link providing reliable, real-time connectivity with sufficient data rate over long distance. However, marine environment causes several challenges, such as high attenuation of radio signal or lack of cellular network coverage. In addition construction of small unmanned vehicles often does not allow to use radio transceivers in an efficient way, e.g. elevating antennae in an Autonomous Underwater Vehicles (AUVs) above the sea level is a challenge. For these reasons practical implementation and validation of network system architectures for coordinated maritime missions is an important step toward autonomous operations of unmanned vehicles.

Mission scenarios described in this paper include tests of a backbone communication link between different types of UV (underwater, surface, aerial). Both, direct connection and data-relay tests results are presented.

The main contributions of the paper are:

- Network system architecture used during operations of 4 different types of UVs, support vessel and on-shore team
- Analysis of a radio link behaviour between Unmanned Aerial Vehicle and support vessel during data-relaying at sea

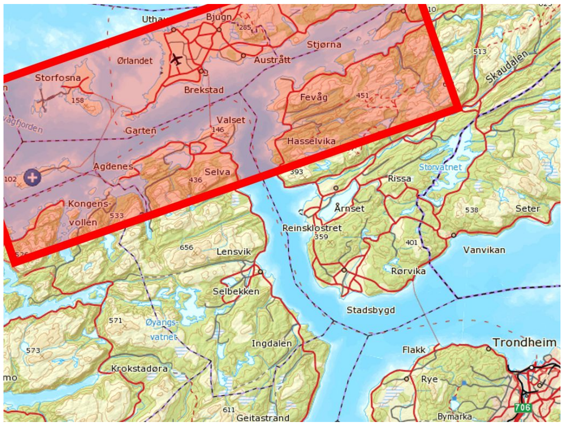

Fig. 1. Area of operation

- Analysis of a radio link behaviour between Unmanned Surface Vehicle and support vessel over long distance at sea
- Description of a communication performance between UVs, vessel and on-shore station, for direct and relayed transmission

Section II of this paper presents vehicles and partners involved in the operation. Section III gives details on network system architecture, while section IV describes communication performance. Discussion is presented in section V.

II. Vehicles

The exercise involved cooperation of 8 departments from 5 institutions. One manned research vessel "Gunnerus" [13], and four UVs were used. These were:

- Hugin by FFI/Kongsberg Maritime – Autonomous Underwater Vehicle (AUV) [14]
- NTNU Skywalker X8 – light-weight Unmanned Aerial Vehicle (UAV) [15]
- Maritime Robotics Telemetron – Unmanned Surface Vehicle (USV) [16]
- Maritime Robotics OceanEye – tethered aerostat [17]

Activities took place near Leksa island, in central Norway (Fig. 1). A mission coordination center was established on the Gunnerus research vessel. Operators of AUV, USV, backbone network and scientists, as well as project coordinators were stationed on-board. Operators of the UAV, were stationed on a coast of Nord-Leksa island, where the UAV could take-off and land.

III. Communication network

III.A Telemetry

Each of the UVs was controlled by a dedicated control station. In order to use common Situation Awareness (SA) platform, telemetry output was provided from the vehicles. In addition ADS-B and AIS receivers were included into the system to visualize position of manned vessels and planes in the area of operation. Having such baseline, a LSTS software Toolchain was selected for a role of the common software platform for SA [18]. The toolset allows to visualize vehicles positions and disseminate that information among involved parties both locally and over the Internet.

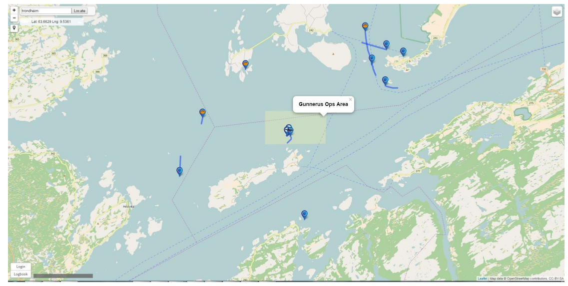

Fig. 2. LSTS Ripples showing vehicles positions and paths

The parsers for vehicles' telemetry were created using several instances of the LSTS DUNE software. When a new set of data arrived, it was packed into a common IMC protocol, and dispatched into the network. Users equipped with a LSTS Neptus C4I software, were able to visualize mission progress and vehicles' positions. Last but not least, information were forwarded to the Internet service called Ripples, which allows to illustrate vehicles' location in a web browser (Fig. 2).

III.B Broadband network

The system operation put some requirements on network system architecture, which simplified diagram is presented on Fig. 3. The architecture uses 6 networks with different IP families:

- Network A & B – backbone networks, using common, licensed radio transceivers. They provide communication between vehicles (A: UAV, USV, Aerostat; B: AUV) and their control stations, as well as test and mission computers.
- Network C – internal network of the Gunnerus vessel, required for the AUV operations. Network was inaccessible for other systems.
- Network D – wired local area network (LAN) with Network F. Providing access to high-level SA data within LAN, and Internet access through Network E.
- Network E – cellular Internet connection on-board the Gunnerus vessel.
- Network F – wireless network (Wi-Fi) on-board the Gunnerus vessel.

IV. Backbone communication link

When vehicles execute missions within a couple of kilometers from each other, commercial-off-the-shelf (COTS), unlicensed solutions working in multi-GHz ISM band, e.g. WiFi, fulfills most of the requirements. However, when distance between vehicles increases, multi-GHz ISM technologies are not sufficient. In many maritime operations cellular networks are not an option, due to lack of coverage. In such situation users can move to lower frequencies ISM links or satellite technology. These however provide very limited bandwidth, may require large antennas not suited for small UVs, and

Vehicle	Selected data-rate	Radio model	Radio type	Antenna elements	Antenna elevation
UAV	3.24 Mbps	CRE2-144-AERO	omni-directional, phased-array	4	UAV altitude
AUV	3.24 Mbps	MBR144	omni-directional, phased-array	4	water level when on the surface
USV	3.24 Mbps	MBR144	omni-directional, phased-array	4	approx. 2 m
Aerostat	3.24 Mbps	MBR144	omni-directional, phased-array	4	Aerostat's altitude
Gunnerus vessel	1.62 Mbps	MBR179	high-gain, omni-directional, phased-array	60	approx. 10 m
NTNU Base	1.23 Mbps	MBR189	high-gain, directional, phased-array	60	few meters above the mean sea level

TABLE I
VEHICLES AND RADIO NODES

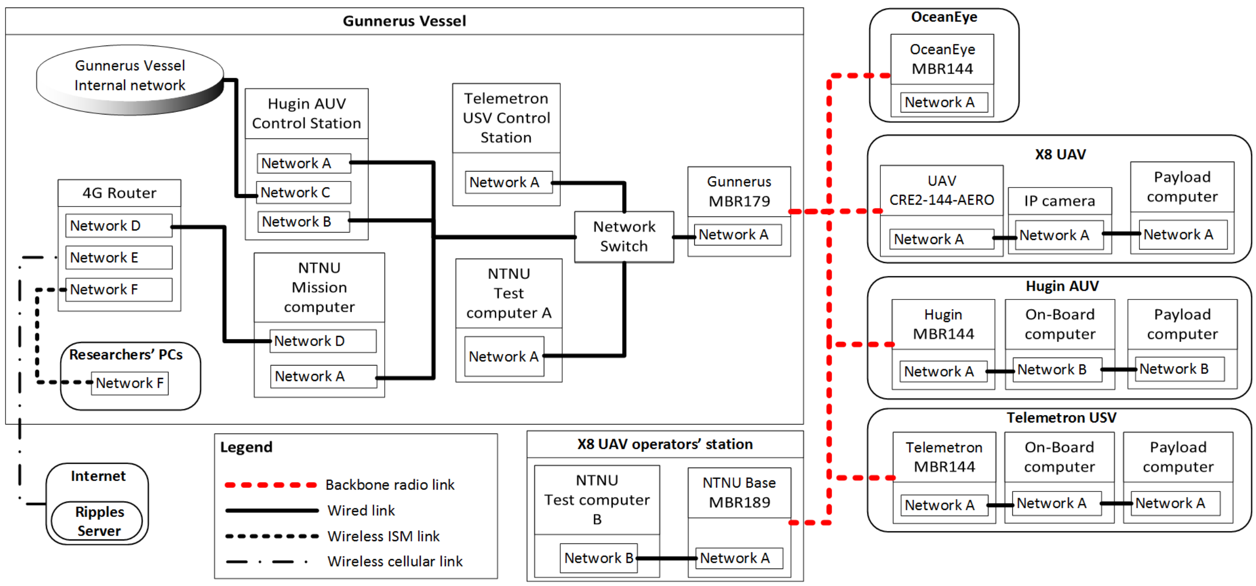

Fig. 3. Network system architecture

additionally, satellite communication can generate extensive costs. Moreover, use of ISM bands may produce significant traffic on a relatively narrow frequency range, that reduce quality of transmission. Another solution is use of a backbone network which utilize licenced-band transceivers to provide connectivity over long distance. In such case, the data-channel is usually less congested, and transmission power can be higher. The backbone network should provide several 10's kilometers range, support data relying and be easily configurable. Additionally, transceivers have to fulfill size, weight and power (SWaP) requirements of various types of UVs.

For the presented experiment the backbone network was created using a Maritime Broadband Radios (MBR) by Kongsberg [9] and compatible Radionor Communications [10] radio.

The radios can be configured in a licensed frequency between 4900 MHz and 5900 MHz. Channel bandwidth is 20 MHz, and nodes use Time Division Multiple Access (TDMA). Maximum total network bitrate can be configured, with a top speed of 15 Mbps. All radio-nodes require common static network configuration, which included MAC and IP addresses of all devices allowed to communicate over backbone network. Available data relaying channel need to be preconfigured as well. Configuration can be changed at any time, but changes should be applied to every node separately.

The network was created between 6 transceivers as seen in Fig. 3, configured to operate at 5230 MHz. Each of UVs had a custom, dedicated antennae array suitable for its SWaP requirements. A list of radio nodes is presented in table I. Every network node was configured with an appropriate timeslot, in which it could transmit. That timeslot directly defined maximum theoretical transmission bitrate. During the experiment more data was transferred from the UVs to the operators than on the other way, therefore link was configured asymmetrically. One of the reasons for the same length of the timeslots in all UVs was data-relay capabilities of the radio. Some scenarios, without Line of Sight (LOS) between end-nodes, used UVs as data-relay nodes. In that case equal transmission time prevent bottleneck effect in the network.

A. Link performance measurement methodology

Network performance tests were controlled from the Gunnerus vessel. Network throughput has been measured using iperf 2.0.5 software. Because the experiment assumed that the data have to be transferred successfully, a TCP protocol tests were used.

Several variables were recorded during the experiment using common timestamp. All vehicles' positions were stored, plus UAV attitude. Log from the backbone radio include values of signal margin and distance between nodes measured using radio waves propagation properties.

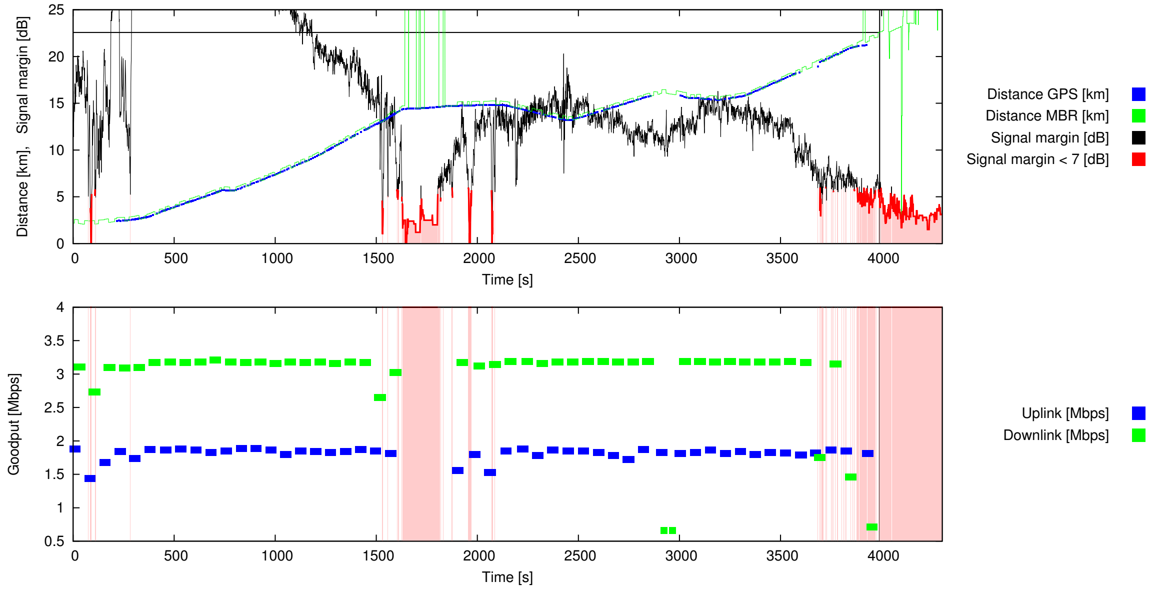

Fig. 4. Vessel to USV communication performance

A dedicated script was invoking two types of iperf measurements. Every measurement was 20 second long, and the order was:

- Measure download speed form the vehicle (downlink)
- Measure upload link speed to the vehicle (uplink)

B. Test: Vessel to USV, direct connection, long range

Long range communication performance was measured between the Gunnerus vessel and the Telemetron USV. While the TCP tests were performed, the Telemetron was moving away from the Gunnerus at speed approx. 20 kn.

49 samples were collected at increasing distance. In average, transfer speed of 2.98 Mbps with standard deviation (σ) of 0.57 Mbps for downlink, and 1.81 Mpbs with σ of 0.09 Mbps for uplink was measured.

The results are illustrated in a Fig. 4. In that figure, the first graph includes two curves representing distance between vehicles. The first curve shows distance calculated using GPS logs, while the second curve marks distance measured by backbone radios themselves. Next, Signal Margin (SM) of backbone radio is presented, with additional shading applied when measured SM was lower than 7 dB. Two lines mark communication loss at a distance of 22.57 km at time=3990 second. At that distance the SM was too low to sustain the connection. An observation cab be made around t=3000s with respect to bandwidth measurement and it should be considered as an outlier. An extensive signal drop in Fig. 4 between t=1500s and t=2100s was caused by the LOS obstruction cased by the terrain. The change is also marked with a separate colour in Fig. 5.

The second graph presents uplink and downlink data rate measured using TCP protocol. The low SM level shading is included on that second graph as well. It is visible, that low SM of the radio influences transfer speed as the implementation of TCP protocol is not the optimum protocol implementation for transferring data over wireless data links. In addition,

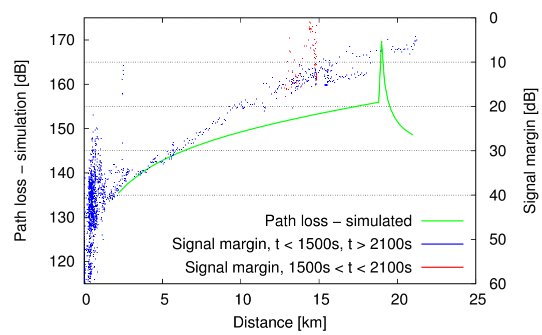

Fig. 5. Vessel to USV communication, Signal Margin over distance and simulated path loss

Signal Margin change over distance is presented in Fig. 5. The figure presents SM points measured by the radio nodes and a theoretical path loss curve. The theoretical curve has been computed using SPLAT! v1.4.2 software, with antenna elevations in table I and settings appropriate for sea conditions: (1) Earth Dielectric Constant: 81.000, (2) Earth Conductivity: 5.00, (3) Atmospheric Bending; 301.00, (4) Radio Climate: 6, (5) Other parameters: default value. The same parameters were used to compute theoretical path loss in Fig. 9. Until the distance reach 6 km, the experimental data path loss follows theoretical line. Later, the difference increases.

C. Test: Vessel to USV via UAV, data-relay

For a next scenario the backbone network was configured to allow data relay from the Gunnerus to the USV via the UAV. The data-relay option allows to extend range of the backbone network and reach places that are beyond direct LOS of the

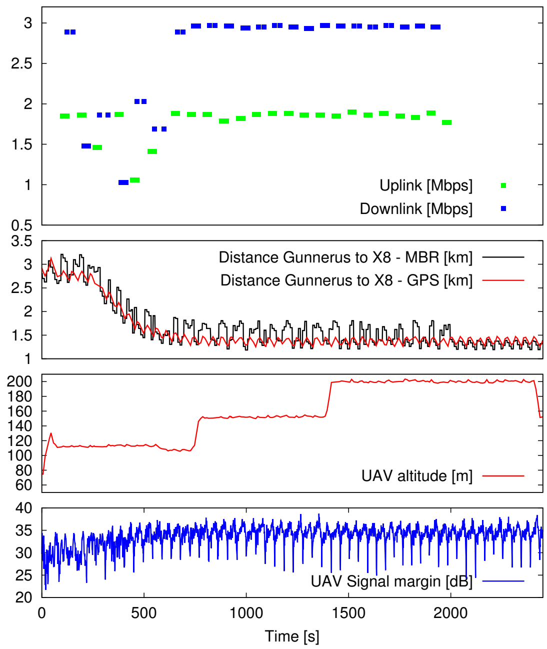

Fig. 6. Vessel to USV via UAV, data-relay communication performance

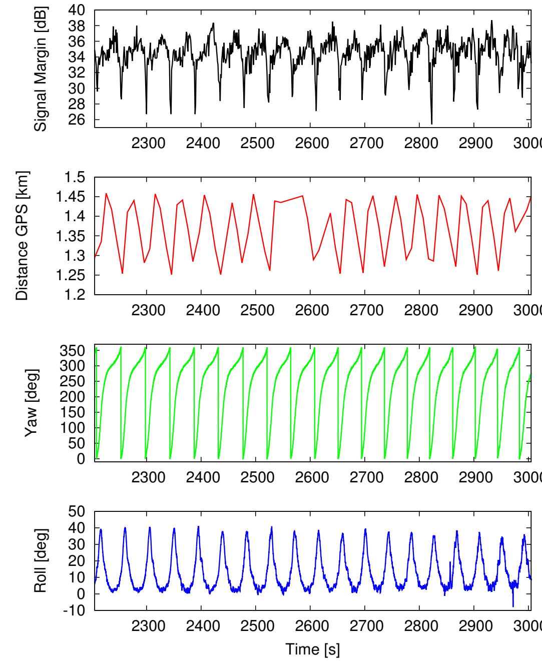

Fig. 8. Vessel to USV via UAV, data-relay, stable flight conditions and Signal Margin

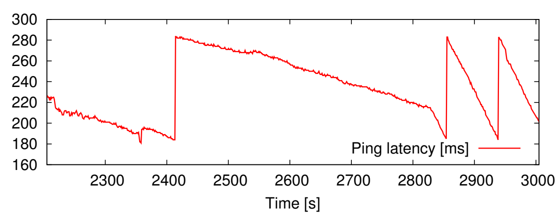

Fig. 7. Vessel to USV communication, ping latency

radio nodes. UAVs realize a function of the relay node role, thanks to their mobility and altitude.

During the experiment, the USV was behind an island, without direct communication with the Gunnerus node. When loss of communication was confirmed by the operators, the UAV took-off. It started loitering at an altitude of a 100 meters for several minutes, then the altitude was increased to 150 and 200 meters.

23 samples were collected. The average downlink speed was 2.66 Mbps, σ of 0.57 Mbps, while uplink speed reached 1.79 Mbps, σ of 0.20 Mbps. Additionally, a network latency has been measured using ping (Fig. 7). The measured latency is between 184 - 283 ms ms in and corresponding with the selected configuration of the TDMA profile and relay set-up. The change in value visible on the Fig. 7 is most likely caused by the radios' transmission timeslots which were not synchronised with the ping data.

Data post-processing has revealed several interesting phenomena (Fig. 6). In the initial phase of the experiment, significantly lower, unstable bitrate can be observed. The most probable cause of this is use of TCP and the implementation of the TCP protocol in the test application. Analysis of data from Gunnerus confirmed that direct connection between Gunnerus and USV was lost, and all data were transferred via UAV. The SM between the UAV and Gunnerus is big enough for stable transmission, even considering plane altitude change and Gunnerus motion, and does not explain that phenomenon. Reason may be the SM between the UAV and the USV, however lack of appropriate log cannot confirm that theory. Another reason could be uncoordinated data transfer from the USV, e.g. video from on-board camera.

SM between the UAV and the Gunnerus shows variations within expected range. These variations are due to the specific antenna element placement on the UAV (Fig. 12) and suggests that UAV's attitude plays a significant role for communication link quality.

Further analysis were performed, over a period of stable UAV loiter, over a single waypoint (Fig. 8).

During the stable loitering flight, the distance between the UAV and the Gunnerus was changing between 1.25 and 1.45 km. Basing on recorded data, presented in Fig. 9, an influence of such a small distance change on SM cannot be determined. Therefore it is neglected, and further analysis assumes that the UAV attitude is the main cause of SM change.

Fig. 10 presents that UAV's roll angle was constantly changing during loiter, most likely due to wind compensation technique. Additionally, the figure includes two vertical lines. First at 309° when nose of the plane was pointing in the direction of Gunnerus vessel. Second at 129° when plane nose was pointing in the direction opposite to the Gunnerus.

Although the graph doesn't allow to separately describe

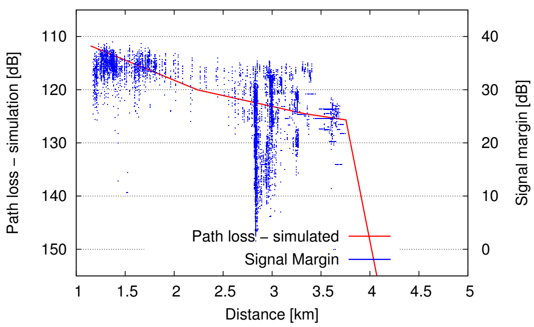

Fig. 9. Vessel to USV via UAV, data-relay, Signal Margin and distance

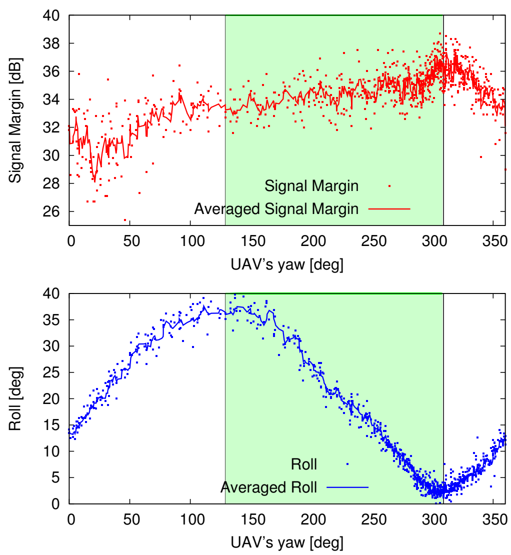

Fig. 10. Vessel to USV via UAV, data-relay, stable conditions, Signal Margin, UAV's roll and yaw. Green shade marks angles when the planes banks toward the vessel

UAV's yaw and roll influence on the SM, some conclusion can be made.

During loitering it is seen that the variation throughout the cycle don't experience the drop of a single antenna null direction, but the phased array system compensates for the effect of antenna element nulls (Fig. 10). This demonstrates that implementations with multiple antenna elements on UAVs are beneficial with respect to most uniform radiation in all directions.

The way the X8 UAV is build (Fig. 12), with electric components behind the antenna, would suggest that SM should drop when plane is backward to the ship, however no such thing can be observed. Therefore it can be assumed that in that specific case, the electric motor influence on communication quality can be neglected. In addition, most likely the plane attitude itself, not the dynamics of its change is a cause of the observed variation in the SM (Fig. 11).

Closer analysis of Fig. 10 suggests that SM is higher when the UAV banks towards Gunnerus – marked on the graph with green shade. The highest SM is reached when nose of the plane

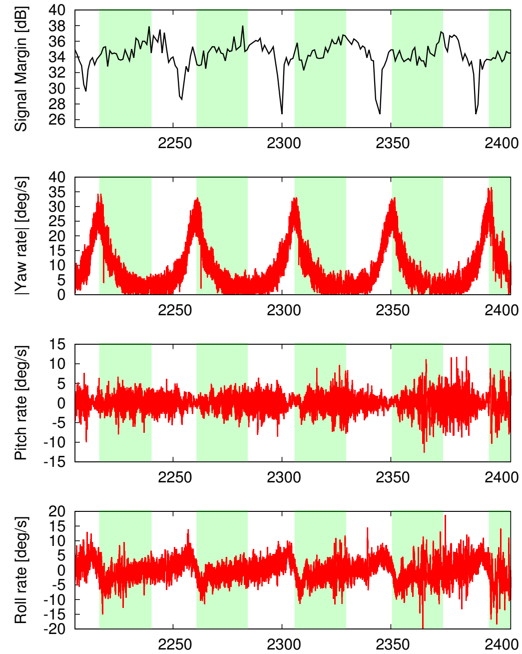

Fig. 11. Vessel to USV via UAV, data-relay, Signal Margin vs attitude rates

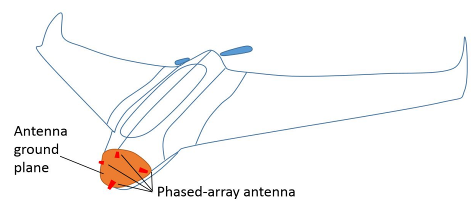

Fig. 12. UAV – antenna location marked with a colour

is pointing in the direction of Gunnerus. The minimum SM is reached when the plane has the Gunnerus vessel approx. 90° on the left, and is banking against the vessel. Such configuration is unfavourable for the antenna radiation pattern.

D. Additional tests

Some exercises limitations, mostly available time, forced very brief tests of network links between the Gunnerus and the Hugin AUV. On a very short distance (tens of meters), 4 samples were collected with the AUV in the water. Average recorded uplink was 2.57 Mbps with σ 0.51 Mbps, while downlink averaged at 1.33 Mbps with σ 0.019 Mbps. Performance may be affected by a low elevation of antenna, which was almost on the level of the water surface. However, at the same time the UAV operators who was placed on-shore, more than 3 km away, reported direct connection between NTNU Base and the AUV.

Even higher transfer reduction is observed when connection between NTNU Base and AUV was relayed via UAV. 6 samples shown downlink speed of 1.43 Mbps, σ 0.35 Mbps, and uplink of 0.87 Mbps, σ 0.32 Mbps.

Communication between NTNU Base and Gunnerus, measured using 37 samples, reached 1.80 Mbps, σ 0.05 Mbps for downlink and 1.09 Mbps, σ 0.04 Mbps for uplink.

Due to operational limitations in airspace access, the OceanEye could be elevated only to the altitude of 130 meters, which did not increase connection capabilities of the Gunnerus node.

V. Discussion

The network system architecture worked very well during the experiment and allowed scientist and engineers to perform planned operations. Results of the performance test show stable and reliable communication. Connection range between the vessel and the USV, exceeded 20 km. It can be assumed that such range will be sufficient for maritime use in many cases. As a reference, the paper [6] suggests that most of the ships have another ship within 30 km, at most 50 km.

Data relay capabilities also proved a good connection speed and high reliability. Observed SM variations seem to be related to the UAV attitude changes and doesn't suggest interference with electric components of the platform.

Connection performance with the AUV was limited, probably due to the antenna elevation. Nevertheless, the result suggests new capabilities for the AUV and its operators.

Lesson learned from the aersotat test is that in the presented scenario, the effect of elevating a less sensitive antenna to 130 m was the same as using more sensitive Gunnerus antenna. The tethered aerostat did not show its full potential during the experiment. However, the design allows to reach altitude of 610 meters [17]. With such elevation it may be a valuable asset to increase the network range.

VI. Conclusions

The papers summarizes a network system architecture, that was used during the exercise which involved 8 individual departments cooperation. UAV, AUV, USV and tethered aerostat, were coordinated from manned vessel and on-shore, to collect scientific data. The proposed system enabled researchers and engineers to fulfill mission objectives. The performance of the backbone network, based on licensed-frequency radio transceivers, has been measured and validated against needs of UVs. Communication link relay over light-weight UAV was presented and its performance validated. The UAV attitude indicate significant influence on Signal Margin level. In all scenarios, including direct and relayed connection, the network was reliable. Operative ranges exceeding 20 km were demonstrated between surface vehicles with the antenna elevations of 2 and 10 meters.

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