# Improving Trails from GPS Trackers with Unreliable and Limited Communication Channels

**Øyvind Hanssen**
Nord University
ohanssen@acm.org

## ABSTRACT

In this document, we explore position tracking in the context of land-based search and rescue operations, where we also may have a limited and unreliable communication channel. This is the case when using APRS (amateur radio tracking) in voluntary SAR services in Norway. We have looked more closely into trails of movements and how to plot these on the map to present informative real-time pictures to the incident commanders. A simple scheme is proposed to improve trails by piggybacking positions at the end of regular transmissions. Experiments show that a significant amount of positions are recovered. In some cases, this can recover useful information, though it depends on the actual situation.

### Keywords

GPS tracking, trails, search and rescue, APRS.

## INTRODUCTION

In emergency response and search and rescue operations, it is useful to be able to track the positions and movements of resources that are out on missions in the field. This is for the safety of the search and rescue (SAR) personnel and better coordination of the operation. It is also desirable to be able to document and analyse the operation after it has finished for the day. This can be done by equipping personnel or vehicles with GPS trackers that transmits information to a service that can present positions and trails (history of movements) on a map. A system for doing this is developed, based on the radio amateur's APRS-network. APRS (Automatic Packet Reporting System) uses VHF (144 MHz) with fairly strong transmitters which gives a fairly long range. On the other hand, the *bandwidth* is narrow and the data capacity rather small. The infrastructure can quickly be extended using mobile repeaters and gateways, it has a low cost, and it is based on voluntary effort.

There is a desire to be able to deploy and use such a system in *remote areas* with limited access to a fixed communications infrastructure. We may also argue that we should be prepared for worst-case scenarios where parts of the infrastructure are down due to some catastrophic event. We may therefore also need to be "*offline*" with mobile and ad hoc arrangements for the reception, storage, and presentation on maps, as well as unreliable communication channels with limited capacity.

A challenge with the APRS system and similar system is the resolution, not much in the spatial dimensions, but mostly in the *temporal* dimension. Since the capacity of the communication channel is limited and it is shared amongst many trackers, we cannot send position updates too often. Also, position reports would frequently be lost because of varying coverage, interference, etc.

According to earlier papers (Hanssen, 2015), there are mainly two types of use of tracking information in such a context. (1) *Real-time tracking,* which helps to see the picture while the operation is in progress. This is for the safety of the personnel in the field and coordination and management of the operation. (2) *Look up trails from a database, typically after a mission or operation has finished.* For example to see where a search has been performed. It could be for documentation, analysis and planning of new operations. It could as well be for research.

The main research question addressed by this paper is *how to improve the quality of trails from trackers moving in the field, where the quality of service of the communication channel can be wea*k. A scheme for doing so, by improving the temporal resolution, is proposed. It seems somewhat obvious that the need for a higher temporal resolution is primarily with the second type of use. In real-time tracking, we are looking at a particular moment in time. To the extent we need trails of movements here, we are typically interested in just the last minutes that lead to the positions right now. We can also (depending on the type of operations) tolerate that positions on the map are some minutes old. Improving the temporal resolution could be useful also here; it will improve the quality of the picture on the map. These claims may be investigated further by asking relevant informants in search and rescue services.

Given the premise that the communication channel has a very limited capacity and is unreliable, we see two possible schemes. *The first* mainly aims at real-time tracking. Here, extra reports and redundant reports from earlier points in time are piggybacked on real-time transmissions. These can be deltas (differences) from the main (real-time) time and position. A piggybacked position report with deltas requires little space compared with a transmission with a stand-alone report. Such redundancy can over time compensate for that a tracker temporarily moves in an area without coverage (radio shadow). In this paper, we focus on the first scheme. An implementation is made and test-runs performed. This method has proved to give a significant improvement in some cases.

*The second scheme* is mostly for looking up trails sometime after. A more detailed trail is stored in the tracker, and when a network (e.g. Wifi LAN) is within range, the tracker automatically detects this and uploads the trail to a server. A tracker is developed, that can automatically connect to Wifi access points (where available) and upload detailed tracks to the server.

The rest of this paper is organised as follows: First, we present some context, i.e. related research in the use of information systems in emergency response and SAR in particular, we introduce concepts of tracking using the APRS systems by radio amateurs. Second, we look at some lessons learned from using tracking and trails in SAR operations in Norway over the past 10 years. By using some example snapshots we illustrate some challenges in the use of trails in APRS tracking in this context. Third, we describe our proposed scheme for improving real-time trails by piggybacking past position reports on transmissions. Fourth, we show some results of testing this. Fifth, we discuss our findings and at last, we conclude.

## BACKGROUND

Information system support for emergency response (Jennex, 2007) is an active field of research and development. Here, spatio-temporal data with geographical information systems (GIS) can contribute significantly to *situational awareness* (Snoeren et. al. 2007; Zlatanova and Fabbri, 2009). This includes the location of incidents, affected areas or buildings, location of rescue teams, victims, shelters, etc. It is useful for decision-makers in the progress of operations as well as planning and debriefing.

A known issue is how to establish a *common* situational or operational picture (Copeland, 2008; Norros et. al. 2010; Wolbers and Boersma, 2013). This concept has several definitions in the literature. There can be challenges in establishing a common understanding of the incident across different organisations and cultures participating in the decision making, or across information-systems supporting decision making.

Dilo (2011) proposes a conceptual model for dynamic, operational information to support emergency response decision making. They distinguish between (1) *situational information* which is about the incident and its effect, and (2) *operational information* which is about active responses, processes, people and organisations involved. They also distinguish between *static information* that exists prior to incidents, like maps, roads and buildings and *dynamic information* produced during an incident. Dynamic operational information includes incidents, events, threatened areas, causalities, teams or vehicles. Some of the information can be *spatio-temporal*, i.e., it contains points in both spatial and temporal dimensions. For instance, the spatial position of objects may change at particular time instants. Through spatio-temporal analysis, one could derive trajectories of moving objects. A data model for *trajectories* is explored, e.g., in (Spaccapietra et. al., 2008) which is a more conceptual background for our more practical investigation of trails in tracking.

### Search and Rescue

For search and rescue operations, a number of information system tools exist for planning, coordination and decision support. The usefulness of GIS in SAR (as well as in emergency response in general) is well known (Ferguson, 2008, Donia, 2009). Advantages include having more updated maps, being able to easier connect between planned and documented efforts, to see areas that are or are not searched, and to integrate information from multiple sources. Another advantage that is mentioned in the literature is the ability to keep track of how rescuers move, which is also the focus of this paper.

GIS tools can also be used to apply search theory and statistical models to help planning the effort and increase the chances of success (Frost and Stone, 2001; Abi-Zeid and Frost, 2005). One could use such tools to visualise the probability of finding the lost person. For example, distance circles may be drawn around the initial planning point (IPP) of the operation, which often is based on the last known position (LKP) of the missing person. The Bicycle Wheel Model (Koester, 2008) is a well-known application of such search theory in land-based SAR. It can be visualised and combined with tools to draw search areas, points of interest, to manage teams and missions, to write operation logs, and to track the position and movements of search teams.

The work described here focuses on one of the many parts of a GIS-based information system for SAR, namely position tracking of teams, vehicles, etc. Several commercial applications exist, providing tracking or fleet maps, often proprietary and limited to single technologies like, e.g., Tetra. We are primarily using amateur radio APRS tracking. Our system aims to be an extensible platform where such functionality may be added as well as alternative data sources. Our project is focused on open source and web-based software, while other solutions are often proprietary or require specific programs to be installed on desktop or laptop computers.

## POSITION TRACKING AND APRS

In this section, concepts of tracking and tracking infrastructure are described. Based on these concepts, we have developed portable trackers as well as a web application for displaying tracking information on digital maps. It is based on Automatic Packet Reporting System (APRS) (Bruninga, 2015) which is an open standard used by radio amateurs worldwide. The adoption of APRS by voluntary rescue services in Norway does not exclude other technologies.

### Tracking Concepts

A *tracker* is a portable device that contains a GPS receiver and a VHF transmitter (or transceiver). It can send its position through some infrastructure to an information system that can process and present the position on a map to support decision-makers in command centres, etc. During operations, a tracker is typically associated with a rescue team or vehicle carrying it. Trackers may be integrated into communication radios and use different technologies and infrastructures (e.g. APRS, AIS, Tetra, cellphone, etc.). Even a smartphone may be used as a tracker using the GPS and a proper app, though there may be issues like battery capacity or coverage. A *position report* from a tracker is usually associated with a time instant. The information system may present the tracker's position at a particular time. In addition, it may present a series of such reports from the same tracker within a certain time-span. We refer to this as a *trail* (or *trajectory*).

### APRS Concepts

In the APRS protocol, *location items* can be either *stations or objects*. Stations have globally unique *identifiers* which typically are *radio callsigns*. Stations transmit position reports in order to update their positions or other associated information. A station typically corresponds to a physical tracker. In addition, stations can report the position of *objects*. Since objects are "*owned*" by stations that report them, they do not need to have globally unique identifiers by themselves. Conceptually, this would imply existence dependency, though, in the APRS protocol, a station can in some cases take over the ownership of objects from other stations. This is useful, e.g., when the station that generated it in the first place stops operating and we still need to keep track of the object.

A *location item* has a (possibly moving) position and is associated with a *symbol* that is sent with position reports. A symbol can be used to indicate what type of item it is or what mission it is assigned, e.g., car, aircraft, boat, rescue-team, etc. A symbol is typically used to select an *icon* when plotting the item on the map.

A *position report* is associated with time, either by *timestamping* it at the source, or timestamping it when received. A *trail* for a given location item is an ordered list (by time) of reports within a given timespan before the last reported position. In a real-time view, this means showing the movements of stations (as lines and points on the map) some minutes back in time.

### Tracking Infrastructure

A tracking system needs an infrastructure to convey and process the stream of information between trackers and the applications where the information is presented. This is also the case for APRS which use AX.25 (Fox, 1984) data packets to send reports over a radio. It uses a single VHF channel and a rather narrow band form of modulation (1200 baud audio frequency shift keying). The APRS protocol (Wade, 2000) defines formats for position reports, as well as for short text messages, telemetry, weather reports, etc. Though it is criticised for being aged and not optimal, it is free to use, an open standard, well tested, widely deployed in the radio amateur community. It is also used on a daily basis. APRS devices are affordable or not too hard to construct. Experiments with more recent digital communications protocols, like LoRa, is also a promising activity among radio amateurs.

*Figure 1* shows how infrastructure consists of several components. Trackers broadcast their information. This is collected by internet gateways (or directly by client apps), possibly after being retransmitted by digital repeaters (often termed 'digipeaters'), to extend the coverage area. The APRS Internet Service (APRS-IS) is a worldwide network of servers that can interconnect the gateways and provide data to applications. The range of repeaters or gateways depends on the topography, antenna height, etc. A range of 50 km is not unusual. The fixed infrastructure can also be extended by deploying mobile repeaters or gateways.

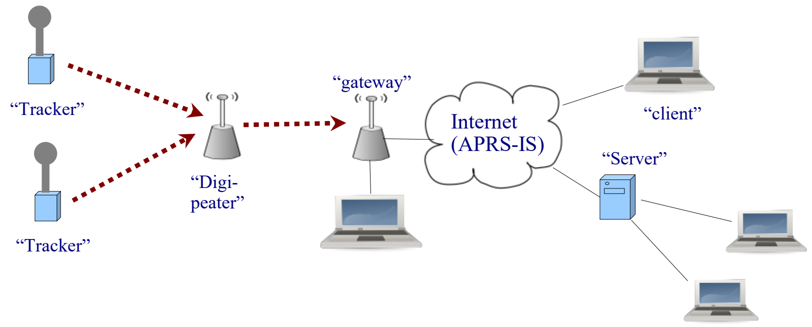


**Figure 1. APRS Infrastructure**

### Related Research on Tracking

Few research papers have been published on APRS tracking in the context of search and rescue. In the context of mobile computing, a fair amount of work has been done on location-services. This includes works on energy efficiency (Kjærgaard et. al. 2009; Farrel et. al., 2007). This can be significant in long missions where there is a strain on the tracker's battery, or where there is little time to charge batteries between missions. *Dead reckoning* (Leonhardi et. al. 2002) is about computing a probable location based on earlier movements. Extrapolation techniques like this is a possible approach to improving trails in our context (if used restrospectively), though probable locations may turn out to be imprecise. They should therefore be marked as such. Detecting *proximity and separation* (Küpper and Treu, 2006) can also be useful when analysing trails.

## LESSONS LEARNED FROM TRACKING IN SAR OPERATIONS

From more than 10 years of experience with tracking in a number of real SAR operations in Norway, we have a significant amount of data, and several lessons are learned. This story is more elaborately described in earlier papers (Hanssen, 2015; Hanssen, 2018). This tracking system has been used mostly in Oslo and Tromsø, but not exclusively. In Oslo, in particular, the operations are often close to the capital, and will often involve more than 20 trackers at the same time. In this section, we show some snapshots from real SAR operations. The improvements tested in the next section are however not yet applied to real operations. This section should indicate that adding trails to the moving points on the map can make the picture more informative, also in real-time tracking, where we are mostly interested in what is going on at the moment. Seeing movements as trails reveals more than just direction and speed. It can indicate intent. Informants say that it is also useful (for the radio operators) to see (from the trail) where radio coverage is problematic. This is useful in planning where to deploy repeaters, etc. However, the examples show that the map can easily be overloaded with "noise" and that there is a potential for various technical improvements.

The results span a broad range from clear and highly informative tracking pictures to more unusable ones. The most important factors that influence the quality of tracking are:

- *Radio coverage*. Trackers use a shared communication channel with limited capacity, trackers may move in areas with weak coverage, and there may be interference, especially where there are a high number of trackers active along with repeaters (to extend the range). If a significant number of transmissions are lost, it will severely affect the quality of tracks.
- *Speed of movement*. Slow movement tends to give better trails since there is more time between moves that need to be reported. Faster movement can be more challenging since updates need to be done more often to give a precise trail. There is obviously a large difference between tracking an aircraft and tracking search teams moving slowly on the ground.
- *Geographic range of movements* (or zoom level). Tracking within small areas, for example in streets in cities, can be more challenging since resolution both in the temporal and spatial dimensions are more significant. Since we can expect that the accuracy of a typical GPS is around 5-10 meters, we need only

worry about GPS errors when zooming in to detailed levels.

- How well the trackers and the presentation system *adapt to varying requirements*. To some extent, trackers can adapt using a so-called *smart-beaconing* algorithm. It adjusts the frequency of updates automatically to match the speed of movement and change of direction. Moving in a straight line is obviously different from moving around corners, making turns, etc.

*Figure 2* shows two rather typical snapshots of real-time tracking in search for missing persons. Tracker positions are labelled (person names are blurred here). The left side is from Oslo showing 20 active trackers and the right side from Tromsø showing 10 trackers. Sometimes the picture can be overwhelming and seem chaotic at first glance. Therefore it is useful to be able to zoom in or to edit the map, for example by changing the length of the trails, using different colours, editing labels or even removing points or trails from the maps that are not significant. This requires skilled and experienced operators that also have time to do this on short notice, which is not always possible to accommodate. We see that the quality of the trails can vary a lot, though they are informative in most cases. If the temporal resolution is too low, for example if moving in areas with bad coverage, having faulty trackers or moving fast from one location to another, this could lead to long straight lines that contribute less to the understanding of what is going on. We see some trails that show clearly what is going on and other trails that could have been more useful if the temporal resolution was improved.

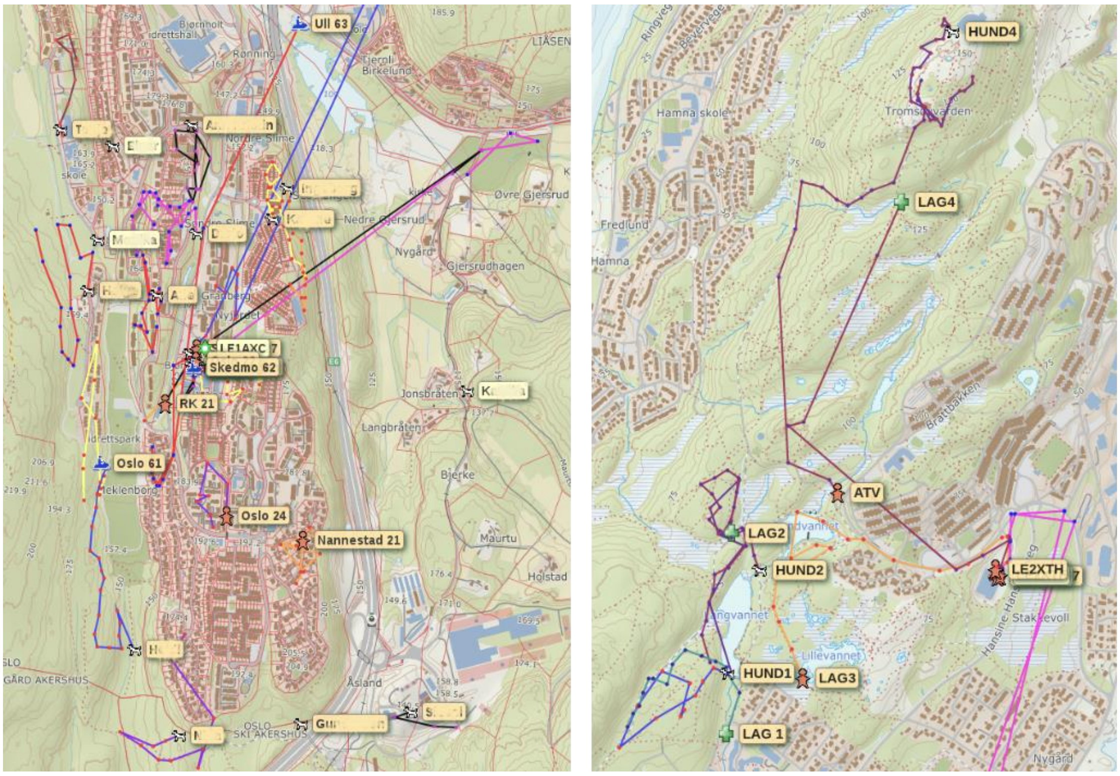


**Figure 2. Tracking in city areas**

*Figure 3* shows an example with 10 trackers (search for a missing person) where trails are not too long and mostly separate from each other. It is easy to see from the picture, what is going on. Here, all trackers moving are search teams climbing steep hills. There is also a marking of an interesting observation (sent from a tracker). The command post is notified about what has been observed, and it can see the position on the map.

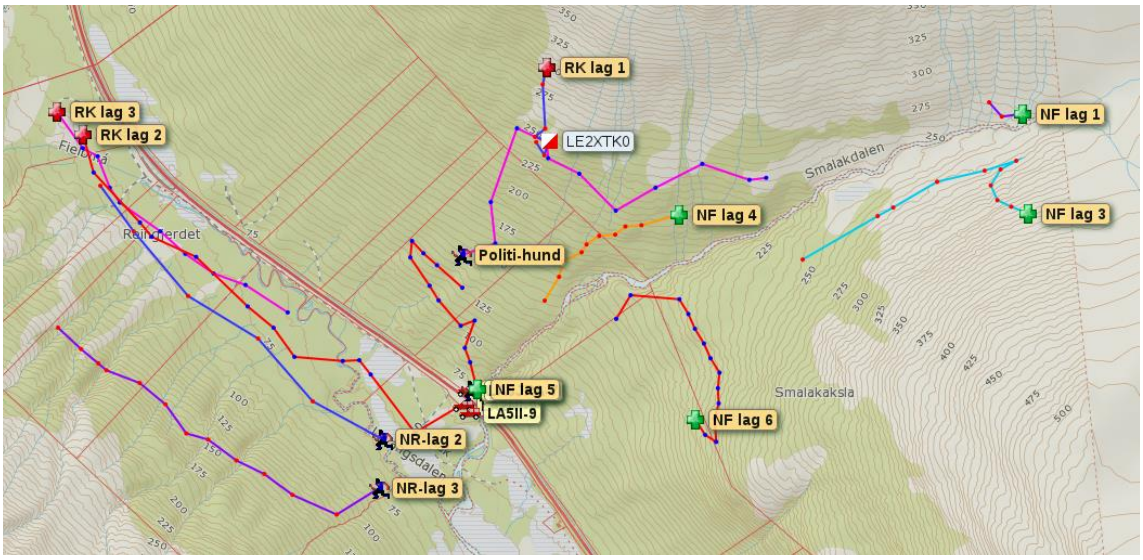

**Figure 3. Search for a missing person in steep hills near Tromsø**

*Figure 4* shows the difference between a useful real-time trail showing an aircraft circling around a mountaintop (left side) and another aircraft search (right side), where we failed to give a clear picture of how the search was performed. However, it is still somewhat useful since we see the area where the flight was done. The reporting frequency and the packet loss of the trackers are almost similar in the two cases, but the flight pattern was simpler on the left side.

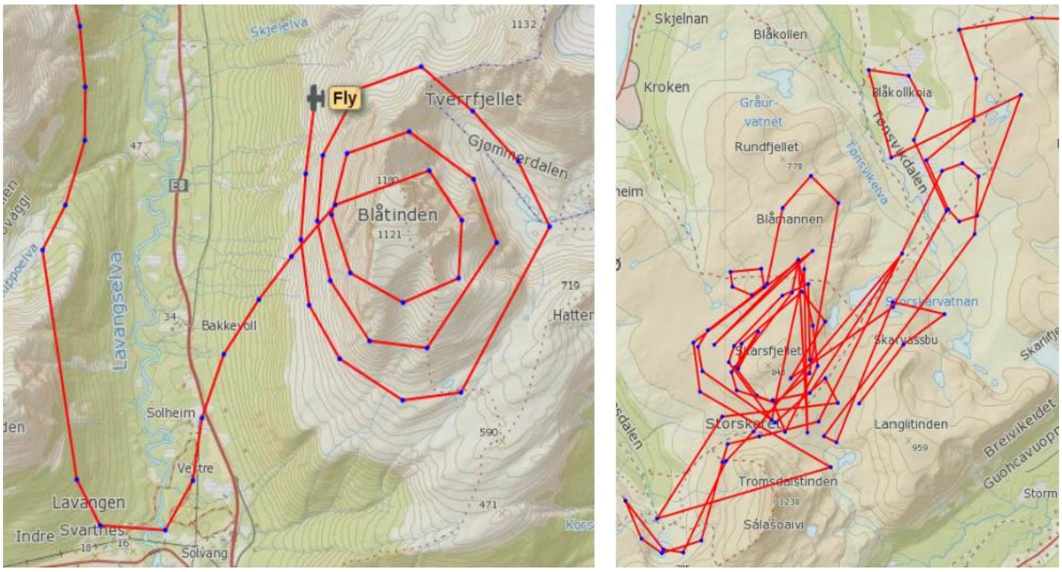

**Figure 4. Aircraft tracking**

*Figure 5* illustrates the power of being able to lookup in a database exactly what we need in order to answer specific questions, typically after the operation has ended. Both tracks are in a mountain area near Tromsø and the frequency of position reports was almost optimal with little loss. The left side shows one single search assignment, where the search team moves up to the area of interest and performs the search there, systematically. The right side shows 6 trackers moving from a common starting point out in different directions. In this case, the lookup was done while the operation was in progress. From this, we could quickly tell if the operation was progressing according to the plan.

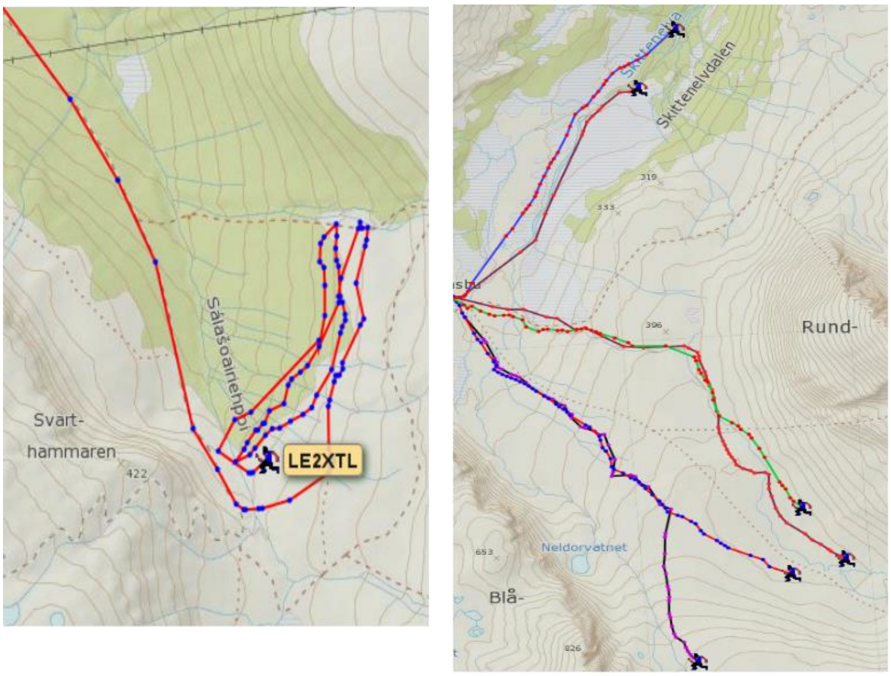


**Figure 5. Looking up trails for specific tasks or missions**

## EXPERIMENT - DESIGN AND IMPLEMENTATION

A tracker prototype has been developed, *the Arctic Tracker*. It is based on affordable modules like the ESP-32 Internet of Things (IoT) microcontroller (Maier, et. al., 2017) and a VHF radio transceiver module. The ESP-32 has Wifi, Bluetooth, a dual-core CPU and enough memory to support fairly advanced applications. It is popular in the IoT and maker communities, and many open-source projects are based on this platform. In this project, a version with 16 MB integrated flash memory is used. This allows storing several hours, even days of trails.

The tracker firmware is designed to transmit position reports with variable time intervals (smart beaconing). An algorithm is designed that decides when to transmit, based on the speed and direction of movement as well as listening on the channel. When the tracker moves faster or changes direction, it transmits more frequently. When it does not move, it may wait for up to several minutes between transmissions. This is user-configurable and can lead to better utilisation of a shared channel. In most cases, it is usually not a good idea to transmit more often than every 20 seconds or so. The time between transmissions should in most cases not be less than 10 seconds. To illustrate why, if 20 trackers share a channel (which is not unusual), each transmission lasts around one second, and each transmission is retransmitted by a repeater, it is obvious that the rate of transmissions must be limited to avoid overloading the channel.

Packets may be lost due to (1) collisions, bit-errors or other interference, or (2) weak or missing signals when moving in areas where it is difficult to reach a repeater or gateway. In the first case, the probability of lost transmissions can be assumed to be evenly distributed and small. In the second case, the probability may be higher during a series of transmissions. In practice, it is difficult to make a general prediction, though we may assume that if one packet is lost, the probability of losing the next one as well is somewhat higher, since we may have moved into an area of weak coverage.

To improve the quality of trails, both in case of lost packets, or where more frequent transmissions would have been appropriate, we have designed and implemented a scheme where each transmission may carry multiple position reports: The current one plus a selection of earlier ones.

*Figure 6* illustrate how we may place position reports on transmissions. It shows a timeline which is usually also a line of spatial movement. It shows how the position reports from earlier points in time can be piggybacked on the current transmission. Depending on the distribution of transmission errors, such a scheme can maximise the probability that a report eventually goes through. In addition, position reports from points in time with no transmissions can be added, allowing for a higher temporal resolution. In our experiments, this is done when changing the direction of movement. If the tracker detects that the direction of movement has changed more than e.g. 40 degrees, it adds the position it had for example 10 seconds ago (illustrated with a star in the figure).

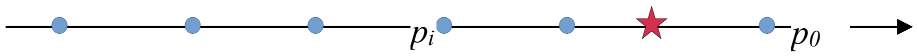


**Figure 6. Position reports and transmissions on a timeline**

### Encoding

The extra or redundant position reports are encoded in the comment field at the end of an APRS standard timestamped position report. We should compress these as much as possible to minimise the overhead. Each report $p_i$ has a main (real-time) position report with a timestamp. When encoding the extra reports, we can use *deltas* of the main report, i.e. the difference between the report in question $p_i$ and the main report $p_0$. This allows us to make these extra reports very compact.

For each extra/redundant position report, we take the timestamp, the latitude and the longitude and compute the difference from the main report of the packet to be sent. A timestamp is the number of seconds since a start date; the delta is the number of seconds between the two reports. The difference between positions is the difference between latitude and longitude coordinates separately; a floating-point subtraction will do.

The timestamp delta is represented as a **12-bit unsigned** integer allowing us to encode time deltas of up to 68 hours, the latitude and the longitude deltas are represented as **18-bit signed** integers by first multiplying the floating-point values with 100,000 and converting to an integer. Since only 18 bits are used, the 18th bit must be used as a sign bit. In this way, a latitude or longitude delta can be up to +/- one degree. A resolution of 1/100,000 degrees is in most cases within one meter.

Each of these is encoded with the *base-64* scheme where each 6-bit chunk is encoded as a character in the set [A-Za-z0-9+/]. The 12-bit timestamp delta is encoded with two characters and the lat/long values are each encoded with 3 characters. The most significant 6-bit chunk first. Then, each report is encoded using only 8 characters.

The comment field may contain a series of such reports, starting with a known prefix, e.g. '**/***' (slash star). So, a comment field of an APRS packet (position report) using this scheme may look like this. The example line below contains 4 timestamped position reports. The first is '**6CACV/04**' where '**6C**' is the timestamp delta, '**ACV**' is the latitude delta and '**/04**' is the longitude delta. If we convert this back to numbers, it represents a delta of 232 seconds, +0.000037 degrees latitude and -0.000178 degrees longitude.

```
/*6CACV/049oAB5/+p+4ABBABV/OAApABE Arctic Tracker
```

### Decoding and Presentation

A platform for presenting tracking information on digital maps, the *Polaric Server*, has been developed and used in real search and rescue operations for years like described in (Hanssen, 2015; Hanssen, 2018). It can decode standard APRS packets, AIS packets, etc. It can store trails in a PostGIS database for later spatio-temporal queries. For this experiment decoding of extra/redundant reports was added. It can recognise such reports in the comment field of APRS position packets, decodes these and inserts them at the proper place in the trails if not there already. This involves sorting the points in the trails with respect to timestamps. *The Polaric Server* is a web-server, it pushes updates to clients in real-time using Websockets and JSON encoding. It can therefore be accessed with most standard web-browsers.

### Protocol Extension

Using the comment field of APRS position reports has been done in an experimental setting. It doesn't exclude having other information in the comment field as well, though different experimental schemes of encoding data in this field, used at the same time, may conflict. For more widespread use, a packet format specifically for this purpose should be proposed as an addition to the APRS standard. A scheme like this is quite efficient with *base-64* encoding using a *character-based* protocol like APRS. A specifically designed *binary* protocol can be made somewhat more efficient, but getting widespread acceptance for such would be a more challenging process.

## TEST RESULTS

The scheme of adding piggybacked (redundant and extra) reports to transmissions are tested the following way: When the direction changes, the smart beaconing algorithm detects a turn and sends a report, an extra report (the position 10 seconds ago) is added. When a position report is generated and transmitted on air, the same report is repeated (in a compressed form) after 2, 4 and 7 transmissions. This means that each report is repeated (sent redundantly) 3 times. This is configurable. Two instances of the Polaric Server are used: One modified instance that can detect the piggybacked reports, and one that cannot, to be able to compare. The tracker is then used in a series of test trips, both driving and walking. *Table 1* shows the results of 7 such trips. It shows that between 26% and 45% of the received position reports (37% on average) are either lost or not transmitted in the first transmission, and then recovered from piggybacked reports on later transmissions.

**Table 1. Recovered position reports**

| Trip | Length | # Recovered | Percentage |
|---|---|---|---|
| Trip 1 (walk) | 1 km | 11 of 30 | 37 % |
| Trip 2 (drive) | 9.5 km | 16 of 36 | 44 % |
| Trip 3 (drive) | 9.5 km | 16 of 61 | 26 % |
| Trip 4 (drive) | 7.7 km | 18 of 54 | 33 % |
| Trip 5.1 (walk) | 2.7 km | 29 of 77 | 38 % |
| Trip 5.2 (walk) | 2.7 km | 25 of 73 | 34 % |
| Trip 6 (walk) | 2.4 km | 18 of 41 | 44 % |
| Trip 7 (walk) | 3.8 km | 31 of 69 | 45 % |

Trip 2, 3 and 4 followed mainly the same route around the town (Mo i Rana, Norway). The algorithm for deciding when to transmit was changed to better adapt to driving speed, so in trip 3 and 4, we transmit somewhat more frequently. It seems to affect the percentage of reports being recovered. Trip 5.1. and 5.2 are the same trip in opposite directions up and down a hill.

The area we operate in is covered by an APRS repeater and a gateway, so these trips were in areas with fairly good radio coverage. Trip 6 and 7 moves in areas where coverage is weaker. We see that even in areas with good coverage, still some transmissions are lost and recovered from later transmissions. It is expected that the recovery percentage will be higher in areas with weaker coverage. *Figure 7* shows trip 2 with (left side) and without (right side) extra/redundant reporting. The recovered reports are marked with green. We see a visible improvement of the trail, i.e. it shows the actual route more accurately.

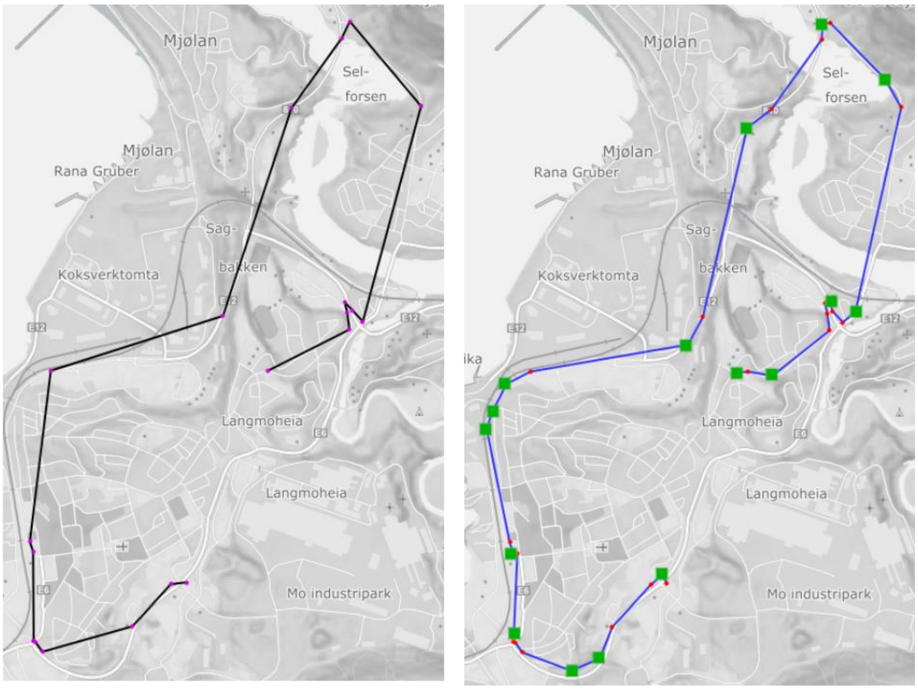


**Figure 7. Trails with and without recovered points (trip 1)**

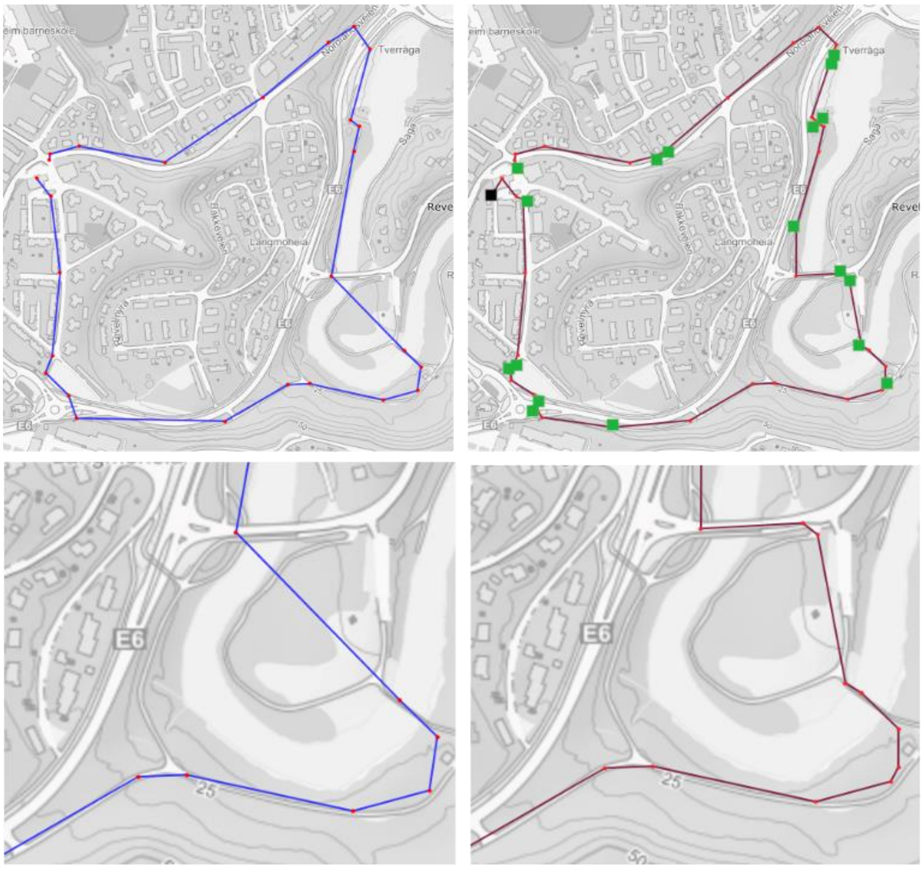


**Figure 8: Trails with and without recovered points (trip 6)**

Sometimes, we would be interested in finding where the tracker has moved in the last minutes. This is near-real-time information we may need while the operation is in progress. The actual route leading to a point can be an educated guess from information on roads, paths, rivers, etc. on the map, but sometimes we may need detailed trail-information from trackers if there is more than one likely route. Even if there is just one likely route, we may need to be reasonably sure. This is information that can be lost when transmissions are lost, but that can be recovered by use of our piggybacking scheme.

*Figure 8* shows trip 6. At the upper right side of the trail, we see that potentially important information is recovered. This part of the trail is magnified at the bottom. Three subsequent transmissions are lost, and there are several possible routes we could have walked. When looking at the map there are two bridges where we could have crossed the river. Even if these three position reports are recovered, we cannot (in this example) be absolutely sure which path we walked (if we assume we follow the paths). However, if we know that position reports are issued when changing direction, we have probably walked the shortest path, which is also a straight line. In the rest of trip 6, our piggybacking scheme doesn't seem to recover important details.

In the other trips we made, we see similar patterns. We see several examples of multiple subsequent transmissions that are lost and recovered, but also many examples of recovered position reports that have little impact on how the command post may understand the movements in the field. In particular, the extra reports, generated when making turns, are often a bit too close to the point where the decision is made. The scheme may be improved by finding the most optimal point to add to the trail. In all cases, the scheme led to smoother trails which can make the picture on the map easier to read.

### Data Analysis

Received position reports are also logged to a database, allowing a range of queries after the trips are made. Two long-distance drives of 700 kilometres each, were made. These trips crossed areas with good and poor coverage, plus some areas without coverage at all. One trip was made on December 20th 2020, where 563 of 1220 reports were recovered, and the return on January 4th 2021, where the tracker was turned off a part of the trip; 319 of 691 reports were recovered. In both cases, the percentage was 46%.

## DISCUSSION

This paper investigates the quality of *trails* of moving GPS-trackers on a GIS map, where the communication channel can be unreliable. Trackers are carried with vehicles, persons or teams that are moving in the field, being assigned missions related to search and rescue. This paper is based on many years of experience with voluntary SAR operations in Norway, as well as designing trackers and GIS software that display information on maps. The focus is on SAR operations on land, possibly with support from aircraft or boats. Trails is a spatio-temporal concept since they describe movements in the time and space domains. A trail is contains information about the movement of an object within a particular time-span. For most practical purposes, it contain a series of points in space, each with a timestamp to tell when the particular position was reported.

We distinguish between (1) *real-time tracking* and (2) *looking up trails stored in a spatio-temporal database,* typically after the operation has finished for the day. The purpose of the first type is to provide an operational picture of what is going on just now and in the past minutes, to help making operational and tactical decisions. Real-time tracking is for the safety of the personnel in the field, and for coordination and management of the operation in progress. It can help incident commanders, answering short-term or medium-term questions. *Short-term questions* may for example be if search teams have observed things of relevance, if they are missing important areas, or if they are about to finish their missions and therefore need transport. A short term question related to safety, can for instance be if personnel are moving into tough or dangerous terrain. *Medium-term questions* can for example be if specific areas are being searched or need to be searched, or questions related to logistics.

The second type of tracking can support medium- or long-term questions, where *long-term questions* include what areas need to be searched, based on an analysis where it is likely that the missing subject is. This may be based on statistical data from past incidents like in (Koester, 2008). For example, after the day has ended, the incident commander and his/her team may need to plan the next day. He/she would also need to document what has been done this day. Such documentation can be used in debriefing, learning and research, but also in explaining to persons close to the victim what has happened and what has been done. The value of the latter should not be underestimated. Losing a person which is close, can be devastating. From my personal experience and others, a typical reaction is to seek information and clarity on what happened and what rescue services have done. A visual explanation is often very helpful in that respect.

### Usefulness of Trails in Real-Time Tracking

We have seen some factors that can affect the quality of trails of real-time tracking like radio coverage, speed, zoom level, or the ability of trackers to adapt their reporting frequency. We have seen a span from highly informative maps to overloaded and chaotic map pictures that are less informative and less intuitive to read. High-quality trails are easier to read and can carry more information than low-quality trails. Trails that by a first glance look chaotic, can in some cases be useful when adjusted and analysed by experienced personnel. However, it can be rather hectic when an operation is in progress, so if the system can automatically help to improve the quality of the picture, it would be useful.

How important is frequent updating? Real-time positions may be several minutes old without being a problem, but this is true to a certain limit. If exceeding that limit, we start to wonder if the tracker has failed or something has happened to the vehicle or team carrying the tracker. We experience in many situations that trackers move into areas without coverage. The system automatically marks a label for a tracker with a different colour to indicate that the time since the last update is longer than a pre-set limit and that we shouldn't trust it to show the position correctly. After even more time, it is removed from the map.

Frequent updating (temporal resolution) seem to be more important when plotting trails of movements (trajectories) and more in after-the-fact analysis than in real-time tracking. However, we have seen some reasons to use trails also in real-time tracking, though shorter in their timespan which is typically immediately before the last position plot. We have also seen (figure 5) that it can be useful to do a database search of longer trails while the operation is still in progress.

### Improving Trails and Map Pictures

Even in real-time tracking, improving the trail some time after can be better than not improving at all. If the team carry more detailed tracks back (stored in the tracker's memory) to the command post after their missions, there is no practical limit to the trail's temporal resolution. Still, it is useful to try to improve tracks when the mission is still in progress. We explore this by designing and testing a scheme where positions are piggybacked on the end of transmissions several times. It the first one doesn't go through, the next may do it. The piggybacked reports are deltas of the main report, and will therefore require little extra space (8 bytes). In contrast, a full APRS report is typically 60 to 100 bytes including addressing. It may take around one second to transmit with 1200 bps speed. In the experiments, 37% of the received reports was recovered this way, some of them because the transmissions were lost. Long-distance trips with partly poor coverage gave 46% recovered reports. This means that a significant portion of reports can be recovered in some cases. We have seen examples of series of 3-4 lost reports were recovered which quickly improved the picture significantly (figure 8). We have also seen examples of less useful recovered positions in areas with good coverage, though some of them may be more interesting if we zoom in. Since it is highly dependent on the situation what is useful, we could probably benefit from optimizing what reports to prioritise using this scheme. An adaptive algorithm for doing this may be a topic for further research.

What we tested here is one approach that tries to get more information through, despite a limited radio channel, by adding redundant and highly compressed reports. Another possible approach is to try to filter the information to deal with information overload issues, as well as trails/points that are not relevant in the particular view. Approaches that are currently explored, include using rule-bases to automatically tag and filter tracking information. This can be used to highlight important facts or remove less relevant information that is regarded as "noise". Alternatively, we may try to extrapolate where it is likely that the tracker has moved, based on the information we have. A goal is to make the picture more informative and easier to read. We should try to find methods that reduce the need for human intervention during the operations, and that can support learning from data. Using machine learning is a possible approach to this.

## CONCLUSIONS

In this paper, we have looked at position tracking in the context of land-based search and rescue operations, where we may have a limited and unreliable communication channel. This is the case when using APRS (amateur radio tracking) in voluntary SAR services in Norway. We have looked more closely into trails of movements and how to plot these on the map, in order to present informative real-time pictures to the incident commanders.

Experiences from numerous past incidents show a variation of trail quality. Factors that affect this include speed, communication channel quality, zoom level and the number of trackers, trackers ability to adapt, etc. For trails that are looked up from a database some time after the operation, it is possible to upload stored trails in trackers when they get back from missions. Improving trails is also useful for real-time tracking, and we have proposed a simple scheme to improve trails by piggybacking extra or redundant position reports on the end of regular transmissions. Piggybacked reports are deltas of the main report and therefore requires little space. Tests indicate that a significant number of reports are recovered with this scheme. Some of them recover significant information of movements, others contribute less to a better picture.

Other schemes for improving trails and map pictures to be explored in future research may include more adaptive position reporting, automatic or semi-automatic filtering of information, and prediction of positions, possibly applying rule-bases, machine learning techniques etc.

## REFERENCES


Abi-Zeid, I. and Frost, J. R. (2005), SARPlan: A decision support system for Canadian Search and Rescue Operations. In *European Journal of Operational Research*, 162(3), 2005, 630–53.

Bruninga, B. (2015) *APRS: Automatic Packet Reporting System*. Retrieved from http://www.aprs.org/

Copeland, J., (2008), Emergency Response: Unity of Effort Through a Common Operational Picture. U.S. Army War College, Available from: http://www.dtic.mil/docs/citations/ADA479583.

Dilo, A. (2011), A data model for operational and situational information in emergency response. In *Applied Geomatics*, 3, 2011, 207-218.

Donia, K. (2009), Custom GIS Tools for Enhancing Wilderness Search and Rescue, Master thesis, University of Redlands, 12-2009, Available from: https://inspire.redlands.edu/gis_gradproj/36

Eide, A. W., Haugstveit, I.M., Halvorsrud R., Skjetne J.H. and Stiso M. (2012) - Key challenges in multi-agency collaboration during large-scale emergency management, *Proceedings of CEUR Workshop*, ISSN 1613-0073, 953.

Farrell T, Cheng R, and Rothermel K. (2007), Energy-efficient monitoring of mobile objects with uncertainty-aware tolerances. In Proceedings of the Eleventh International Database Engineering and Applications Symposium.

Ferguson D. (2008), GIS for wilderness search and rescue. In *ESRI Federal User Conference*, Washington DC.

Fox, T. L. (1984), AX. 25 amateur packet-radio link-layer protocol: version 2.0, American Radio Relay League, Newington, CT, USA.

Frost, J. R. and Stone L. D. (2001), Review of Search Theory: Advances and Applications to Search and Rescue Decision Support, U.S. Coast Guard Research and Development Center Report No. CG-D-15-01.

Hanssen, Ø. (2015), Position Tracking in Voluntary Search and Rescue Operations, In *Proc. 12th International Conference on Information Systems for Crisis Response and Management*, ISCRAM 2015, ISBN 978-82-7117-788-1.

Hanssen, Ø. (2018), Position Tracking and GIS in Search and Rescue Operations, In *Crisis Management*, Holla et. al. (eds), IntechOpen, ISBN 978-953-51-6103-5.

Jennex, M. E. (2007) Modeling Emergency Response Systems, In *proc. 40th Annual Hawaii International Conference on System Sciences* (HICSS 2007), 22–22.

Kjærgaard, M. B., Langdal, J., Godsk, T. and Toftkjær, T. (2009), EnTracked: energy-efficient robust position tracking for mobile devices, In *Proc. Mobisys '09: The 7th International Conference on Mobile Systems, Applications, and Services Kraków Poland*, ACM, ISBN 978-1-60558-566-6

Koester, R. J. (2008), Lost Person Behavior: A Search and Rescue Guide on Where to Look - for Land, Air and Water, Dbs Productions.

Küpper, A. and Treu, G. (2006), Efficient proximity and separation detection among mobile targets for supporting location-based community services. *Mobile Computing and Communications Review*, 10(3):1–12.

Leonhardi, A., Nicu C. and Rothermel K. (2002), A map-based dead-reckoning protocol for updating location information. In *Proc. 16th Int. Parallel and Distributed Processing Symposium.*

Maier, J., Sharp, A. and Vagapov, J. (2017), Comparative Analysis and Practical Implementation of the ESP32 Microcontroller Module for the Internet of Things, in *Proc. 7th International Conference on Internet Technologies and Applications,* IEEE, ISBN 978-1-5090-4815-1.

Norros L., Liinasuo M. and Hutton R. (2010), Designing Tools for Emergency Operations: New Method of Parallel Augmented Exercise. In *Proc. 28th Annual European Conference on Cognitive Ergonomics*, ACM.

Snoeren, G., Zlatanova, S., Crompvoets, J. and Scholten H. (2007) ,Spatial Data Infrastructure for emergency management: the view of the users, In *Proc. 3rd International symposium on Gi4DM*, 22-25.

Spaccapietra, S., Parent, C., Damiani, M. L., de Macedo J. A., Porto, F. and Vangenot C. (2008), A Conceptual View on Tracjectories, In *Data & Knowledge Engineering*, 65(1), 2008, 126-146.

Wade, I. (ed.). (2000), APRS Protocol Reference. Protocol version 1.0, Tucson Amateur Packet Radio Corp (TAPR).

Wolbers, J. and Boersma, K. (2013), The Common Operational Picture as Collective Sensemaking. In *Journal of Contingencies & Crisis Management*; 21(4):186–99.

Zlatanova, S. and Fabbri, A. G. (2009), Geo-ICT for Risk and Disaster Management, In *Scholten, P. H. J., Velde, D. R. van de, Manen, N. van (Eds.), Geospatial Technology and the Role of Location in Science*, GeoJournal Library, Springer, 239–266.