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LOCALIZATION OF INTERROGATORS WITH A 1030/1090 MHZ SPECTRUM MONITORING SYSTEM

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Abstract

We present a new method for localizing Mode S Secondary Surveillance Radar (SSR) interrogators, which compared to previous work only requires the reception of aircraft transponder replies using one receiver on the ground. Because too high interrogation loads can lead to the suppression of targets, there is an interest in localizing unknown interrogators. To test the proposed localization method a proof-of-concept spectrum monitoring system based on Software Defined Radio (SDR) receivers was implemented. Results obtained from data recorded with the spectrum monitoring system show that Mode S SSRs at distances of up to ca. 320 km could be localized with a distance error <3.5 km, based on a recording of 5 s duration. Additionally, we also present results for load monitoring of aircraft transponder reply rates.

Keywords: Secondary Surveillance Radar, Localization, Spectrum Monitoring

1. Introduction

Secondary Surveillance Radars (SSRs) and Automatic Dependent Surveillance Broadcast (ADS-B) are two main surveillance technologies that are used for aeronautical surveillance and for tactical air traffic management. All aircraft transmit their surveillance replies at 1090 MHz while interrogations by SSRs take place at 1030 MHz. The monitoring of the 1030 MHz and 1090 MHz frequency bands plays an important safety-relevant role, as too high loads can lead to the suppression of targets. Under Article 6 of the Commission Implementing Regulation (EU) No 1207/2011 [1] there is an obligation on spectrum protection in the european airspace.

Since interrogators have a large coverage, the presence of additional, unknown interrogators can trigger replies from aircraft transponders in a wide area. Therefore, it is desirable to be able to detect and locate such interrogators. We propose a new method for the localization of SSR interrogators with mechanically rotating, directional antennas. To test the method and to perform load monitoring, a proof-of-concept spectrum monitoring system was implemented, using receivers built from off-the-shelf Software-Defined Radios (SDRs) and a central data-processing unit. The obtained SSR localization performance and load monitoring results are presented in section 4.

Interrogation signals sent by a civil SSR consist of two pulses of the carrier frequency of 1030 MHz spaced 8 µs or 21 µs apart for Mode A or Mode C, respectively. Reply signals of an airborne transponder consist of a sequence of pulses of the carrier frequency 1090 MHz. In case of a Mode A interrogation all transponders will reply with the transponder code (‘squawk’ code), while in Mode C all transponders will reply with the barometric height. Mode S interrogations allow selective addressing of aircraft transponders in order to reduce the reply load. Mode S uses Differential Binary Phase-Shift Keying (DBPSK) Modulation on 1030 MHz for interrogations, while transponder replies again consist of a sequence of pulses of the carrier frequency 1090 MHz.

Besides ground based interrogations, additional sources of load are interrogations and replies due to the Airborne Collision Avoidance System (ACAS), which operates on both frequencies, and ADS-B messages emitted by transponders on 1090 MHz, which are transmitted spontaneously without being triggered by interrogations. Finally, military radars also use the same frequencies.

Typical approaches for the localization of transmitters are multilateration (MLAT) based on the time difference of arrival (TDOA) of received signals and triangulation [2]. MLAT based on TDOA uses the difference in arrival time measured at multiple receiver locations, while triangulation is based on direction finding (e.g. using directional antennas) at multiple receiver locations. The localization of SSR interrogators with the MLAT method is challenging, since SSRs emit a narrow beam pointed in a specific direction at a certain time instant, which makes the simultaneous reception of the signal at multiple locations difficult. With triangulation the SSR signal does not have to be received simultaneously at the receiver locations, but it still limits the operational range of the localization to distances with a direct line-of-sight to the SSR, if the receivers are located on the ground.

Previous work on the localization of SSR interrogators in [3] describes a localization method requiring multiple receivers installed in Unmanned Aerial Vehicles (UAVs) or aircrafts and which is based on a nonlinear least-squares estimation using the Time of Arrival (TOA) and the Position of the airborne receivers. In [4] a localization method using only one receiver based on the TDOA between the interrogator and aircraft transponder signals is presented, however, the method requires direct reception of the interrogator signal, which limits the range for interrogator localization.

In this paper we present a new method for localizing SSR interrogators based on the Mode-S all-call reply messages (downlink format 11) [5] sent by aircraft transponders. Results from field tests are also presented. Compared to [3] the method only requires one one ground-based receiver, while compared to [4] it can provide localization of interrogators in a potentially wider area, since only the reception of aircraft transponder replies is required.

2. Proof-of-concept Spectrum Monitoring System Setup

2.1 Overall Spectrum Monitoring System

Figure 1 shows the implemented spectrum monitoring system, which was used to collect measurement data for testing the localization of SSRs and for load monitoring. It consists of three spatially distributed receivers based on SDRs, which store the received data with GPS-exact time stamps for later central processing.

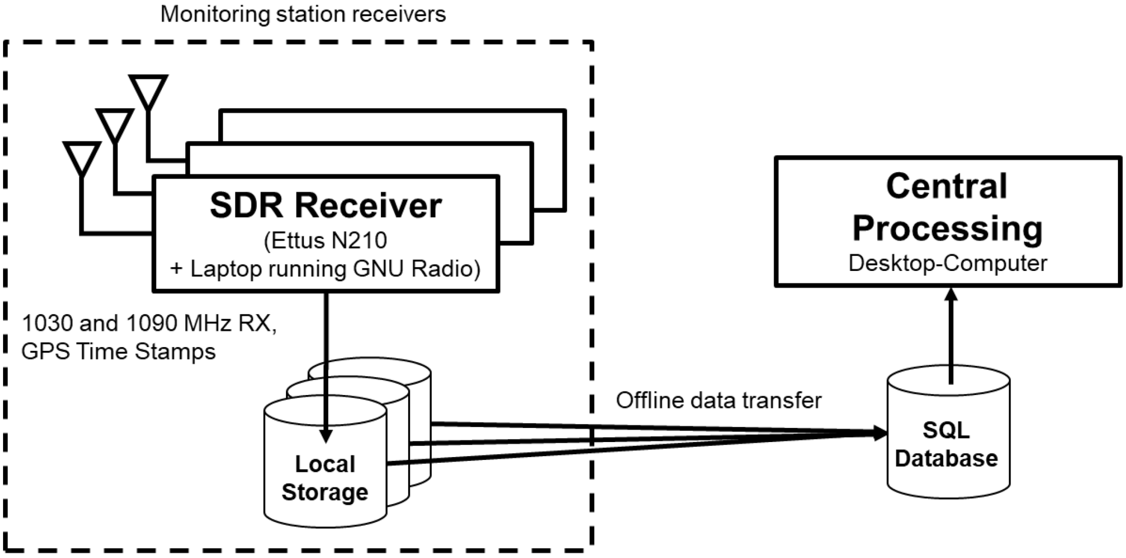

Figure 1 - Overview of the implemented 1030/1090 MHz spectrum monitoring system

The high-sensitivity receivers use an omni-directional antenna covering frequencies from 1030 MHz to 1090 MHz. The data from the three receivers is then transferred offline to a central SQL-database for further processing. The central processing allows offline listing, filtering, statistical analysis and load determination based on the received packets, as well as localization of Mode S SSR interrogators and localization of aircrafts. In this paper, we focus on the localization of SSR interrogators and load monitoring.

2.2 Spectrum monitoring Station Receiver

Each spectrum monitoring station receiver is based on an Ettus/National Instruments N210 SDR Receiver connected to a high-performance laptop with a fast Solid State Drive (SSD), which performs demodulation and decoding of the messages using our own receiver implementation in GNU Radio. The SDR uses a GPS-disciplined oscillator for accurate local oscillator frequency generation and time stamping of the received messages.

Figure 2 shows the overall spectrum monitoring station receiver block diagram. In order to achive a high sensitivity, an RF frontend was developed which is based around Low-Noise Amplifiers (LNAs), bandpass filters and power limiters. The bandpass filters No. 1, 4 and 9 remove unwanted emissions in other frequency bands (e.g. mobile network signals), the limiters 6 and 11 protect the SDR from excessive receive levels from the transponder when the receiver is installed in an aircraft and the LNAs 2, 5 and 10 improve the sensitivity of the receiver. Since the limiting operation can create unwanted harmonic frequencies, the limiters are followed by bandpass filters No. 7 and 12.

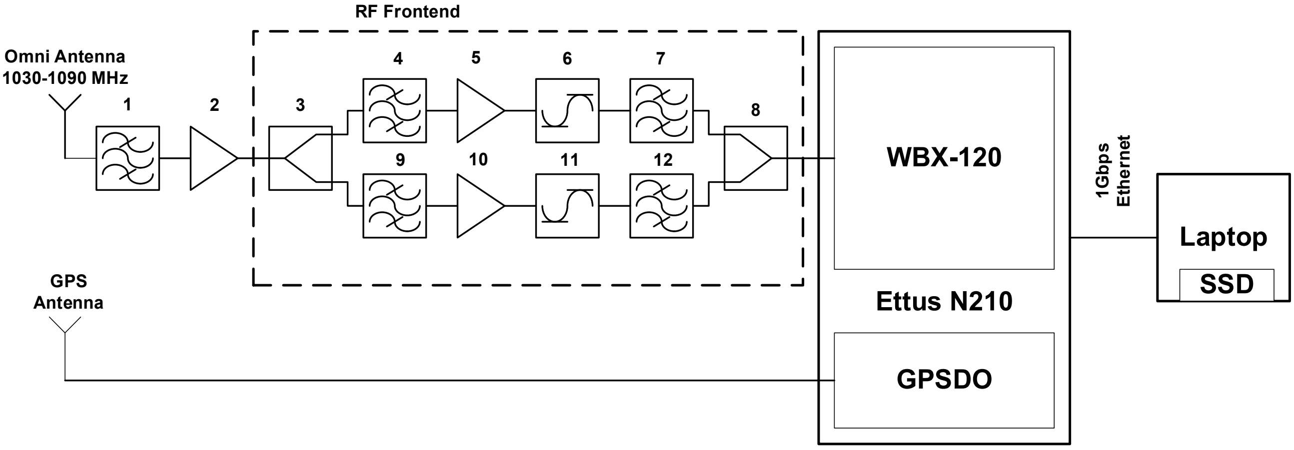

Figure 2 - Block diagram of the spectrum monitoring station receiver

The RF-Frontend consists of the following elements listed in Table 1.

Table 1 - Components of the RF frontend

Component No. in Figure 2	**Description**
1	Bandpass filter 1015 – 1105 MHz
2	LNA, Noise Figure (NF) 0.5 dB
3, 8	3-dB splitter / combiner
4, 7	Surface Acoustic Wave (SAW) bandpass filter 1030 MHz, bandwidth 10 MHz
5, 10	LNA, NF 0.5 dB
6, 11	Limiter 0 dBm
9, 12	SAW bandpass filter 1090 MHz, bandwidth 10 MHz

To measure potential frequency deviations of transponders and interrogators, a receiver bandwidth of 10 MHz was used at both 1090 MHz and 1030 MHz. For Mode A/C and Mode S a receiver sensitivity of ca. -96 dBm was measured in the lab on both frequency bands, which is better than the typical sensitivity of an SSR receiver of around -80 dBm [6].

The spectrum monitoring station receivers store the following information locally:

- GPS-time stamp of message reception (arrival) time
- Message type and message data
- Received signal strength (RSSI)
- Carrier frequency offset (CFO)

RSSI and CFO measurements are not used for the localization of interrogators and load monitoring.

3. Localization of SSRs and Load Monitoring

3.1 Introduction

There are two fundamental types of interrogators based on the radiating characteristics: SSR Interrogators with mechanically rotating, directional antennas and omni-directional interrogators, typically used for the localization of aircrafts with the MLAT method. In the following, the localization of SSR interrogators based on Mode S messages is discussed.

The limitation to Mode S should not restrict the potential use, as normally SSRs use both Mode S and Mode A/C interrogations. The localization of omni-directional interrogators could e.g. be performed using MLAT based on TDOA.

3.2 Localization of SSR Interrogators

The proposed localization method for Mode S SSR interrogators assumes that directional antennas, which rotate at a constant angular velocity, are used at the SSR. The method uses a geometry-based approach and relies solely on aircraft replies to determine the planar (two-dimensional) interrogator position. It uses the Mode S transponder all-call replies (downlink format 11), which is triggered by SSR all-call interrogations. All-call replies are used since they contain the interrogator code, which can be in the form of an interrogator Identifier code (II) or a surveillance identifier code (SI), overlaid on the parity check field. This allows for filtering of all-call replies based on interrogator codes for subsequent localization.

The localization method consists of the following high-level steps:

1. Determine the interrogator antenna angular velocity v_I based on all-call replies by aircraft transponders to the same unknown Interrogator
2. Using the time difference of all-call replies between two aircrafts Δt, interrogator antenna angular velocity v_I and aircraft positions, the interrogator location can be restricted to a circle which passes through the locations of the two observed aircrafts and the unknown interrogator location
3. Perform step 2 for another pair of aircrafts to get a second circle
4. Obtain the unknown interrogator location as the intersection of the two circles

These steps are explained in more detail in the following with the help of Figure 3.

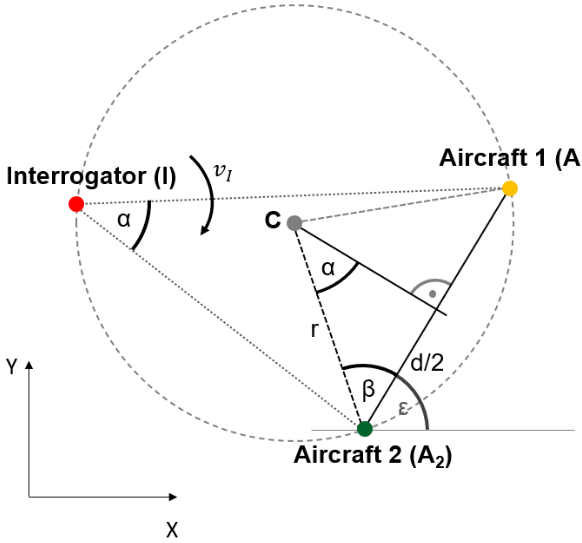

Figure 3 - Localization of rotating SSR interrogators using replies from multiple aircraft transponders

The angular velocity of an interrogator antenna $v_I = 2\pi/T_0$ is determined by calculating the histogram from the time differences between all-call replies of the same aircraft transponder to that specific interrogator identifier. At integral multiples of the revolution period T_0 a distinct spike in the histogram can be observed.

Since there may be more than one interrogator with the same identifier triggering replies by aircraft transponders, additional filtering is necessary before responses qualify as resulting from a specific SSR. This is especially true for the case with interrogator identifier code zero (II=0) which is reserved for mobile radars. A transponder is assumed to be within the main beam of the SSR if at least 4 responses to that interrogator identifier are received within a 200 ms timeframe and there is a 100 ms gap with no replies on either side. If this condition is met at 3 consecutive revolutions of the SSR, the responses qualify for calculating the position of the interrogator as further described.

First, by restricting the method to interrogators with a fixed unknown position (I_X, I_Y) and with the assumption of a clockwise antenna rotation (which is typical), the following angles can be determined from the central angle theorem by using the time difference Δt between two selected aircrafts beeing within the main beam of the interrogator

$$\alpha = v_I \cdot \Delta t \tag{1}$$

$$\beta = 90 - \alpha. \tag{2}$$

The time difference Δt is determined from all-call replies of the two selected aircrafts, measured from center to center of the transponder response sequences which qualify for calculating the position of the interrogator.

Secondly, the distance d between the two aircrafts is calculated using the position (A_{1X}, A_{1Y}) of the first aircraft A_1 and the position (A_{2X}, A_{2Y}) of the second aircraft A_2. These positions are obtained from ADS-B messages from the aircraft transponders and can be interpolated between ADS-B messages. Subsequently, the radius r of the circle passing through the unknown interrogator location and the two selected aircrafts is determied

$$d = \sqrt{(A_{1X} - A_{2X})^2 + (A_{1Y} - A_{2Y})^2} \tag{3}$$

$$r = \frac{d/2}{sin(\alpha)}. \tag{4}$$

Next, the location (C_X, C_Y) of the center of the circle is determined

$$\varepsilon = atan2\left(\frac{A_{1Y} - A_{2Y}}{A_{1X} - A_{2X}}\right) \tag{5}$$

$$C_X = cos(\varepsilon + \beta) \cdot r + A_{2X} \tag{6}$$

$$C_Y = sin(\varepsilon + \beta) \cdot r + A_{2Y} \tag{7}$$

where $atan2(\cdot)$ is the four-quadrant inverse tangent function. It can be shown that the above method is also applicable when $\alpha > 90^0$.

Once two such circles have been determined, the interrogator position can be obtained from their intersection points. Since two circles with distinct center locations have either zero, one or two intersection points and because both circles must pass through the unknown interrogator position, in practice there will be either one or two intersection points. If the selected pair of circles intersects in two points, only one will correspond to the interrogator location. This ambiguity can be avoided by intersecting only circles which pass through a common aircraft. Thus, the intersection point at the location of the common aircraft can be discarded, in which case the other intersection point (I_X, I_Y) corresponds to the estimated interrogator location. It follows that a minimum of three individual aircrafts are required for the localization of an SSR.

In practice, more than two circles can be used and the estimate of the interrogator location can be determined as the centroid $(\bar{I}_X, \bar{I}_Y)$ of the interrogator locations obtained from individual pairs of circles, as described above.

The proposed method could in principle also be applied to the reception of all-call interrogations sent by SSRs, but this would limit the operating range for the localization, as at least three ground based receivers have to be able to receive the interrogations. A better approach in this case would be to use airborne receivers, similar to the method in [3]. An advantage with this would be the higher number of packets available for localization, as in our method the number of available all-call replies is limited due to the typical use of all-call lockouts by SSRs.

In the following, a brief high-level discussion of the impact and possible mitigation of individual error terms on the the SSR localization performance follows.

Angular velocity of interrogator antenna: Assuming that the anglular velocity v_I of the interrogator antenna is constant, the error of the estimate of v_I, determined from interrogator replies, can be reduced by increasing the observation interval.

Aircraft selection, time difference Δt: Using an error propragation analyis by partial-derivation of equation (6) or (7) with respect to α, it can be shown that $\alpha_{opt} = \pi/2$ minimises the impact of the error of α on the estimated center of a circle (C_X, C_Y). From this it follows that selecting two aircrafts with time difference $\Delta t = \alpha_{opt}/v_I = T_0/4$ between them being in the main beam of the interrogator is optimal. Since accurately measuring Δt is challenging, this helps reducing the impact of the error of Δt.

Aircraft positions: The ADS-B status message contains the Navigation Accuracy Category - Position (NACp), which can be used to select only reports with low uncertainty. For example, by selecting only messages with NACp ≥ 9, the horizontal estimated position uncertainty is < 30 m.

Transponder reply delay: Since the time difference Δt ist used, only the reply delay tolerance of 0.25 µs for Mode S transponders [5] is relevant. Since this value is very small compared to the angular velocity of the interrogator antenna and the aircraft speed, the impact can be neglected.

Time-stamp error at monitoring station receiver: Since GPS-based timestamps are used, the error (typically < 50 ns) is again very small and neglegible compared to the angular velocity of the interrogator antenna and the aircraft speed.

3.3 Load Monitoring

According to [1] ground-based interrogators must not produce excessive interrogations, in order to limit interference and congestion on the frequencies 1030 MHz and 1090 MHz. The compliance criterion is based on the measurement of transponder replies per second due to all received interrogations. The limits on the reply rates are taken from [5], which are summarised in Table 2.

Table 2 – Transponder reply rate limits

Transponder Capability	**Maximum number of replies per second**
Mode A/C	500
Mode S short Transponder	50
Mode S long capable Transponder	16 Mode S long out of 50 Mode S

The measurement of the load is performed by calculating the statistics in Table 2 for the replies filtered for a specific aircraft address. The aircrafts selected for analysis should have a high RSSI, in order to receive as many replies as possible from the replies actually emitted by the aircraft transponder.

4. Measurement Results

4.1 Localization of SSR Interrogators

Figure 4 shows the results of localizing SSR interrogators according to the method in section 3.2 in the area of Zurich airport based on 5 s of recorded data, while the interrogator antenna angular velocity v_I was determined from several minutes of observation. Three spectrum monitoring station receivers were used at distances between 20 km to 30 km from Zurich airport to improve reception, after duplicate messages had been removed. The green dots correspond to the intersection points of two circles passing through a common aircraft. The interrogator positions $(\bar{I}_X, \bar{I}_Y)$ are marked by red dots and were estimated as the centroids of the intersection points of circles-pairs, determined over the 5 s recording. These positions agree well with the known interrogator locations marked by violet pentagon shapes.

As a measure of accuracy, the distance error between the estimated centroid interrogator position and the known position is used. For the precision the Distance Root-Mean-Square Error (DRMS), based around the estimated centroid interrogator position, is used [7]. The DRMS are shown as red circles in Figure 4. As listed in Table 3 for the SSRs A, B and C, the distance errors are in the range of 433 – 612 m, with relatively large DRMS values of up to almost 4000 m. The SSRs B and C are located 300 m apart, both of which have been localized.

Figure 4 - Interrogator localization in the area of Zurich airport (map: swisstopo)

Table 3 –SSR localization performance

SSR	**Distance error [m]**	**DRMS [m]**
A	433	3953
B	612	3229
C	519	1441
D	210	5071
E	2037	4532
F	2225	3237
G	3495	4608
H	1530	5986

Figure 5 shows the localization of SSR interrogators in a wider area. It can be observed that the estimated interrogator positions (red dots) still correspond relatively well with known interrogator positions. The SSR H, at a distance of ca. 320 km from the spectrum monitoring receivers, could be localized with a distance error of ca. 1.5 km and a DRMS of ca. 6 km, as listed in Table 3. For all known interrogator locations, the distance error stays below ca. 3.5 km.

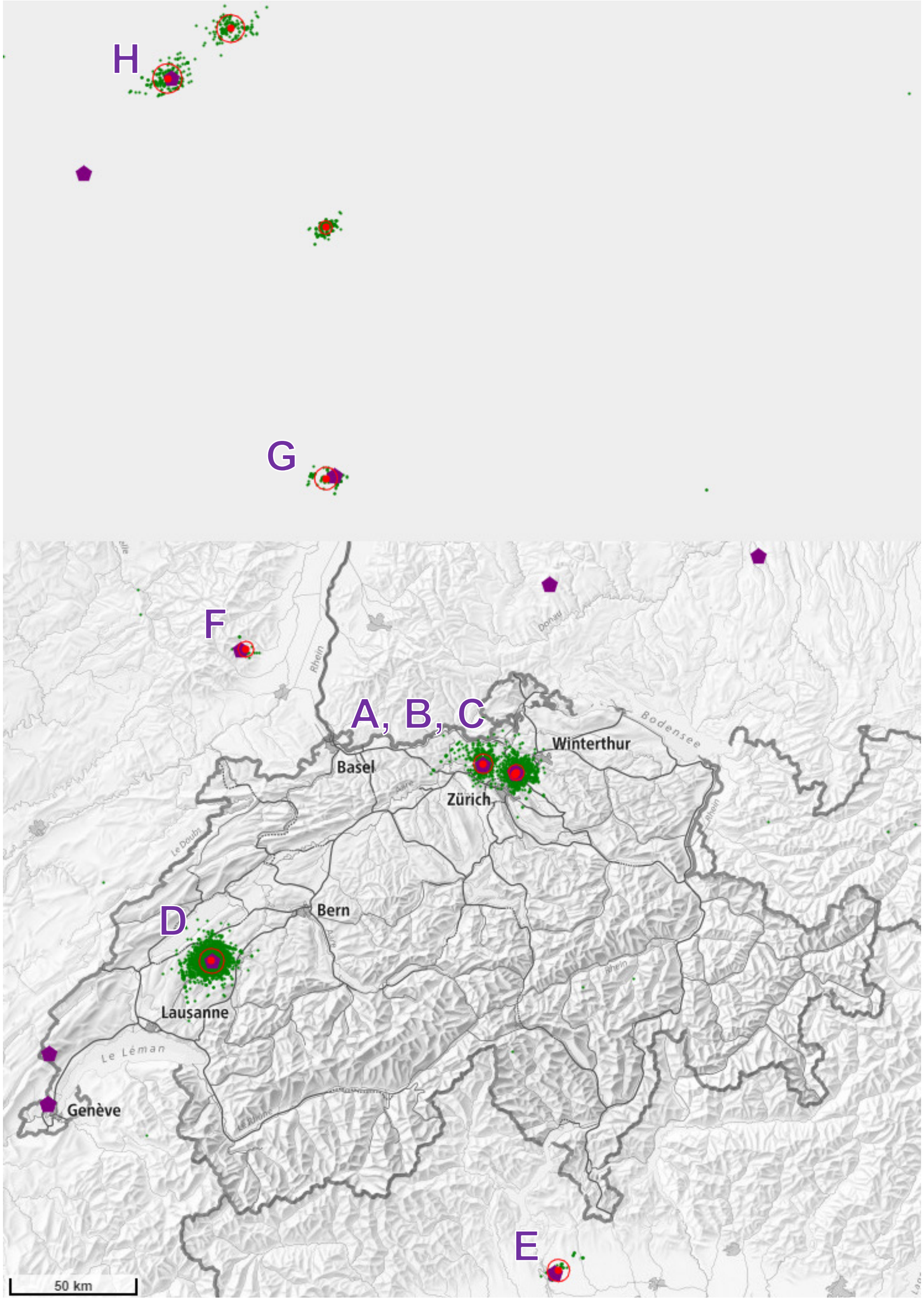

Figure 5 - Interrogator localization in a wide area (map: swisstopo)

Some known interrogator locations have not been identified with this particular 5 s recording, but have been identified in other recordings. This can e.g. occur if not sufficient all-call replies for a particular interrogator code are present.

4.2 Load Monitoring

Figure 6 shows the Mode S transponder reply rate of a selected aircraft for the duration of approximately 30 min, during which it passed over the receivers at an altitude of 38000 ft. The spectrum monitoring station receivers were again located at distances between 20 km to 30 km from Zurich airport. While the Mode-S short messages only once severely exceeded the limit of 50 messages/s (see Table 2), there were 8 occurencies with more than 16 Mode S long messages per second.

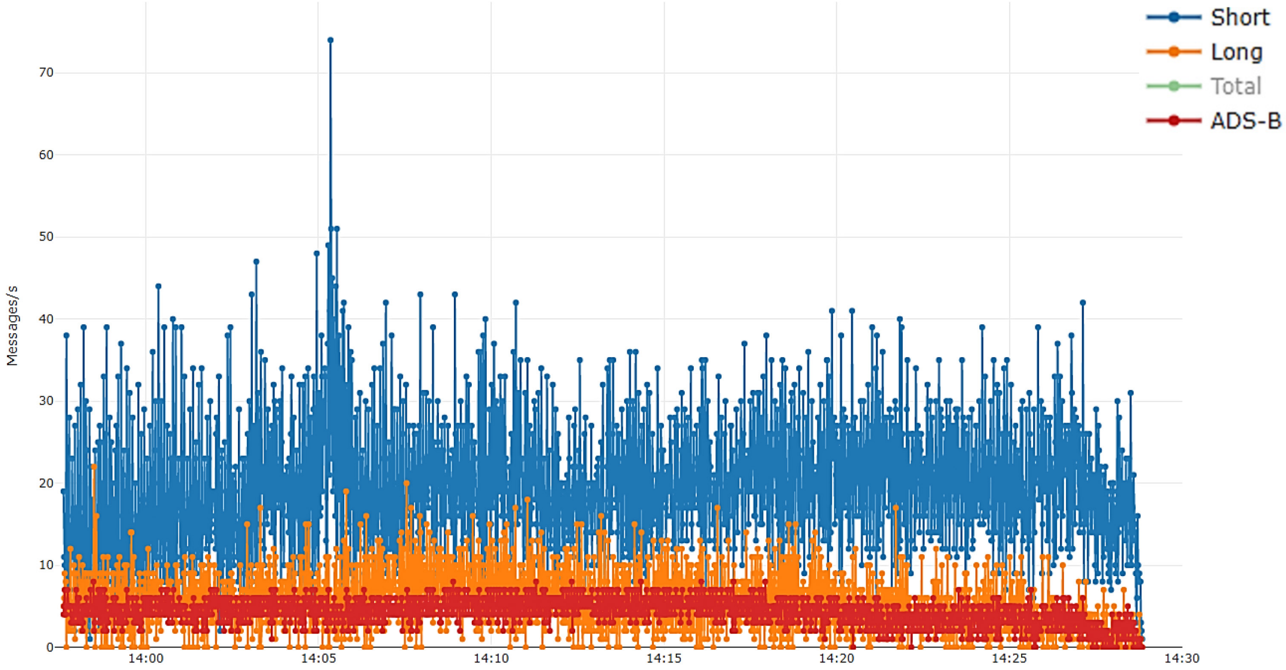

Figure 6 – Mode S transponder reply rate of a selected aircraft

The above behavior is a typical example for the message load we observed from several hours of measurement data recorded on individual days. During our monitoring-tests all aircraft transponder reply rates stayed most of the time within the limits and no transponders were detected which severely exceeded them on a regular basis.

5. Conclusions

While the accuracy in the range of ca. 450 – 3500 m achieved from recordings of transponder replies does not allow a precise pin-pointing of SSR locations, we believe that the proposed localization method is useful for practical applications, in particular since it only requires one receiver on the ground, it has a wide operational range and it can operate with relatively short recording durations.

Based on the same recordings, load monitoring of the transponder reply frequency 1090 MHz was performed. During the monitoring over several hours of measurement data no significant exceeding of the limits was detected, while occasional exceeding of the limits could be observed.

The spectrum monitoring stations to acquire the recordings were implemented using off-the-shelf SDRs, which obtained a high sensitivity while being flexible for future extensions.

Future work on the localization of SSRs could focus on improving the filtering and processing of transponder replies for the case when replies to different interrogators with the same interrogator code are present. Another area could be the expansion of the localization performance analysis.

Finally, the method could be extended to the localization of mobile interrogators, by introducing tracking of the estimated interrogator location.

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7. Copyright Statement

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