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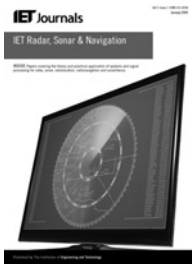

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Design and performance evaluation of a mature FM/DAB/DVB-T multi-illuminator passive radar system

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Abstract: Passive radar (PR) systems use the target illumination by third-party transmitters, for example, from broadcast or cellular base stations, for target detection and localisation. Since PR does not use an own transmitter, it can be installed and operated at low cost and it is hard to detect and jam. These advantages and the increasing maturity of PR technology has led to growing interest in these systems over the last years. However, until now most PR systems have been rather experimental set-ups tailored to a single frequency band or implemented as laboratory test devices. This study in contrast describes the design, implementation and performance evaluation of a multi-band, multi-illuminator PR system developed at near-production stage. Starting out from a FM-broadcast-based approach, the step to DAB-based and DVB-T-based operation has already been made. As a result, a fully mobile FM/DAB/DVB-T multi-band PR system is now available, offering maximum flexibility for measurement campaigns with air, ground and sea targets. Experiments with a great variety of third-party transmitters and arbitrary transmitter-target-receiver geometries have been conducted. The design considerations and the resulting PR system concept are described, and the results of representative measurement campaigns with different types of ground and aerial targets are presented.

1 Introduction

The detection and localisation performance as well as the overall technical maturity of experimental passive radar (PR) systems is steadily improving [1–4]. Starting out from early FM-broadcast-based systems [5, 6], the evolution to mature DAB-based and DVB-T-based systems [7] has been achieved [3, 4]. In this paper, a multi-illuminator PR system exploiting FM, DAB and DVB-T transmitters with cross-band data fusion is introduced. The system is integrated into a compact vehicle and thus provides a modular and versatile platform to

- evaluate and compare the performance of different algorithmic approaches to target detection, ranging, two-dimensional (2D)- and 3D-localisation,
- evaluate the performance of different signal processing concepts and receiver structures,
- obtain experience with typical effects of radio wave propagation, bistatic target reflection properties and interference in the FM, DAB and DVB-T bands,
- evaluate different approaches for target tracking, data fusion and multi-sensor fusion,
- explore the functionality of illuminators with different properties and distinct receiver locations in order to steadily enhance mission planning,
- demonstrate the performance of PR systems and evaluate different approaches for data presentation in order to optimise the man–machine interface (MMI) for passive sensors,
- pave the way to operational PR systems for use in air surveillance, air traffic control and in applications for ground and sea target detection.

In the following sections, the basic design considerations and the system concept including a sophisticated mission planning tool are described. Additionally, the results of extensive measurement campaigns with different types of aerial and ground targets are presented.

2 PR system architecture

2.1 Basic design considerations

The goal of this design effort was to build a mature PR system mainly for airspace surveillance with a range and resolution comparable to that of an active air surveillance radar, that is, a circular coverage area with a diameter in the order of 200 km and a target location accuracy in the order of 100 m, as well as additional ground and sea target detection applications. In central Europe, the following transmitters of opportunity supporting this goal given in Table 1 can be identified [4, 7, 8].

FM radio is the world's most widespread broadcast standard. It is well suited for PR long-range coverage due to its large transmit power. FM transmitters typically show a comparably wide antenna elevation characteristic and depending on their location often do not use a downtilt of the beam. Thus, FM provides a good airspace illumination even for

Table 1 Third party illuminators

Broadcast network	Frequency band, MHz	Transmitter bandwidth	Typical transmitter power (EIRP)
FM radio	88–108	0–100 kHz[a]	10–100 kW
DAB radio	174–240	1.5 MHz	1–10 kW
DVB-T (television)	470–790	7.6 MHz	1–100 kW

[a]Variable bandwidth depending on transmitted content.

high altitude targets. However, as target range accuracy and range resolution depend on the signal bandwidth, both are limited due to the low and varying bandwidth. This can be improved, for example, by multi-static illumination in combination with adequate data fusion and tracking algorithms. Also, several FM signals at different frequencies but originating from the same transmitter station can be combined to obtain increased bandwidth and thereby to further improve the range resolution [9].

DAB radio is available throughout in most parts of Europe and in many countries worldwide. It uses a coded orthogonal frequency division multiplexing (COFDM)-type of modulation, which provides a constant bandwidth of about 1.5 MHz, thus enabling sufficient range measurement accuracy. The transmit power is significantly lower than with FM radio, therefore the transmitter station's spatial density is typically much higher. In Germany and in some other countries, DAB is implemented in single frequency network (SFN) configurations, that is, all transmitters of a certain network use the same transmit frequency, which in general leads to a received signal where multiple time- and phase-shifted copies of the transmitted signal are superimposed. Whereas in a DAB radio receiver this is easily compensated by channel estimation and equalising, and a PR receiver faces the additional problem that it is not possible to unambiguously associate a target reflection to a certain transmitter station. This ambiguity has to be solved by adequate tracking algorithms, for example, by multi-hypothesis tracking (MHT), and thus leads to higher complexity of the PR signal processor. However, due to the large transmitter density and the medium directivity of the elevation pattern a very good multi-static illumination of ground, sea and air targets in the medium to lower airspace is ensured.

DVB-T has replaced analogue TV transmission in most European countries. It also uses a COFDM-type of modulation and provides a large bandwidth transmit signal at a high transmit power. Many DVB-T transmit antennas show a small elevation beamwidth and some use an additional downtilt of the antenna beam. Thus, DVB-T provides a good illumination mainly in the lower to medium airspace as well as on ground and sea. The large bandwidth leads to a very high range resolution which in most cases results in a good range accuracy of detected targets. The transmitter spatial density is lower than in DAB networks. However, in Germany and in some other countries DVB-T is – like DAB – operated in a SFN configuration. Thus, the advantages of high power, high bandwidth and inherent multi-static target illumination can potentially be exploited by a carefully designed PR system.

The detection process in PR systems is typically accomplished by extracting the target reflection, that is, the time-shifted copy of the transmit signal, from the total received signal which is largely dominated by the direct signal (DS) from the transmitter. This is one of the greatest challenges in PR design as the difference of the received power levels between DS and target reflection may well exceed 100 dB. The time difference of arrival (TDoA) between these two signal components results in a territorial ellipsoid which defines all possible locations of this specific target, see Fig. 1.

To provide the unambiguous target location in 3D, two different methods can be applied. These are shown in Fig. 1. The first possibility is to use an efficient direction finder (DF) capable of providing a precise measurement of the target direction. Intersection of ellipsoid and bearing vector leads then to the 3D position of the target.

The second approach is based on multi-lateration, which describes the intersection of multiple TDoA ellipsoids generated by the use of different dislocated illuminators. To enhance localisation accuracy and eliminate ghost targets caused by multiple intersection points, more than two illuminators are required or an additional DF has to be applied. In this case the high bearing angle accuracy requirements as mentioned above can be eased.

As a result of the studies preceding the PR built-up, the ellipsoid intersection approach shows to be more robust and accurate than the DF approach, but requires adequate algorithms and sufficient processing power to cope with multiple-target scenarios and to run in real-time.

The PR coverage area, that is, the 3D section of the surrounding airspace where the PR can detect, locate and track targets with a given radar cross section (RCS) compliant to predefined performance measures, is dependent on many parameters:

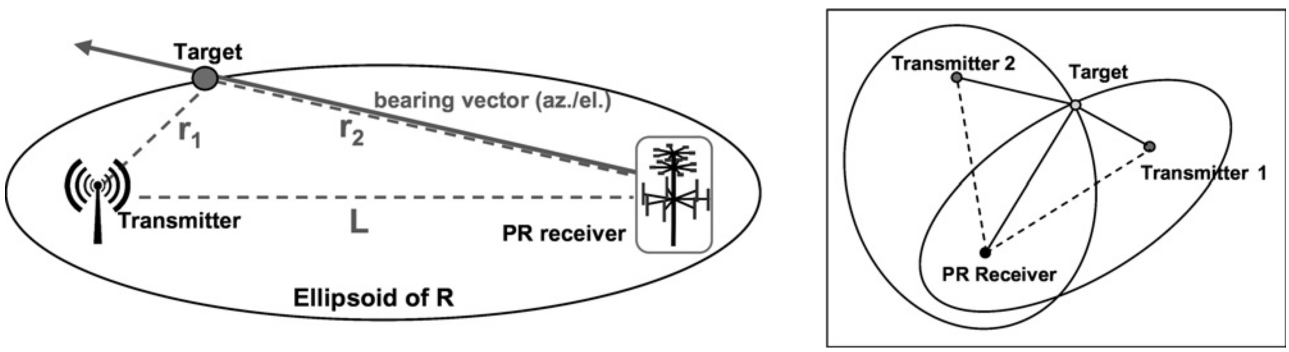

Fig. 1 *Target location by direction finder (left) and multi-lateration (right)*

Fig. 2 *Passive radar van and operator consoles*

- PR hardware implementation, for example, antenna system, receiver sensitivity, receiver linearity;
- PR algorithms for DS suppression, target detection, multi-band and multi-transmitter data fusion, target location and tracking;
- PR advanced modes of operation, for example, dynamic transmitter switching (DTS), adaptive integration times or dual-mode target location (see above);
- number, location and characteristics of the exploited transmitters, for example, frequency band, transmit power, antenna azimuth and elevation characteristics;
- PR location, shadowing and multi-path effects between transmitter and target as well as between target and PR receiver, spatial bistatic clutter distribution with respect to each one of the exploited transmitters.

To predict the PR coverage area or to optimise the 3D outline of the coverage area with respect to a given surveillance task, all of the above parameters have to be taken into account. Typically, this can only be accomplished by an overall systems model comprising a transmitter database, geographic information system (GIS) data, wave propagation models and an accurate model of the PR hardware and algorithm design. This kind of model is especially necessary to establish a mission planning tool to predict optimum PR installation locations, to select transmitters and to enable advanced operation modes like real-time DTS.

2.2 PR system implementation

All design considerations for the PR system were directed towards a mature and fully mobile assembly. It therefore covers analogue FM broadcast as well as DAB and DVB-T waveforms with a single mast multi-band antenna. The system is able to process multiple FM transmitters simultaneously as well as DAB SFNs and DVB-T SFNs in real time. Electronic equipment and operator's workstations are integrated in a specific PR van which comprises the integrated, extendible antenna mast system. The innovative system design enables full mobility and flexible deployment in all kinds of terrain. Fig. 2 shows the van in transport mode (left side) and operational mode (middle). For transportation the lifting arm is retracted and the antenna elements are removed by quick fasteners. On-site system installation can be realised within 30 min. An additional picture gives insight into the PR van and shows the operator's work environment with three independent work stations.

The system architecture of the multi-band PR system is shown in Fig. 3 [10]. The integrated multi-band antenna system uses 21 elements distributed on three elevation levels. This antenna structure provides 360° azimuth coverage and enables 3D bearing detection. The antenna comprises an integrated calibration system for improved bearing accuracy. The FM and DAB subsystems use seven antenna elements and seven channel direct sampling and downconversion receivers. DVB-T is received and processed by direct downconversion in 14 channels with antennas on two elevation levels for additional elevation angle bearing detection. Real-time processing is implemented on commercial PC hardware based on standard quad-core processors. An enhanced MHT system resolves ambiguities resulting from the multi-illuminator situation for digital SFNs and fuses FM, DAB and DVB-T detections and range–rangerate tracks to optimise spatial coverage and localisation performance. The MMI consists of three separated displays. The signal processing engineering console allows the display of, for example, antenna amplitude levels, the frequency spectrum of the received signals as well as the processed range Doppler maps. In addition, a tracking engineering console is realised for the display of intermediate tracking results and further internal parameters. The fused output tracks are visualised on the professional and end-user-oriented operator console visualisation system (ViSys). ViSys is a modern air surveillance MMI which is based on a standard product for the German improved air defence system (GIADS). For reference purposes, a commercial ADS-B receiver is part of the system. Its tracks can be displayed on ViSys for real-time comparison between actual air picture and the PR performance.

To use the existing infrastructures like the already mentioned GIADS, the PR output data is mapped into standard ASTERIX protocol formats. Active radars typically transfer their data in cat.48 (incl. cat.34) for plots respectively cat.62 for tracks.

Unlike active radar plots, the individual bistatic PR plots consisting of bistatic range and Doppler depending on the transmitter do not allow a location of the target in 2D/3D. Thus, the transmission of real PR plot data is meaningless to standard multi-sensor tracking systems and operators. Hence, the same tracker output data is used for coding track positions as 'pseudo plots' in cat.48 as well as track positions including velocity and heading as tracks in cat.62.

Since common visualisation tools do not provide track history information for cat.62, the additional parallel display of 'pseudo plots' in cat.48 visualises both, the high update

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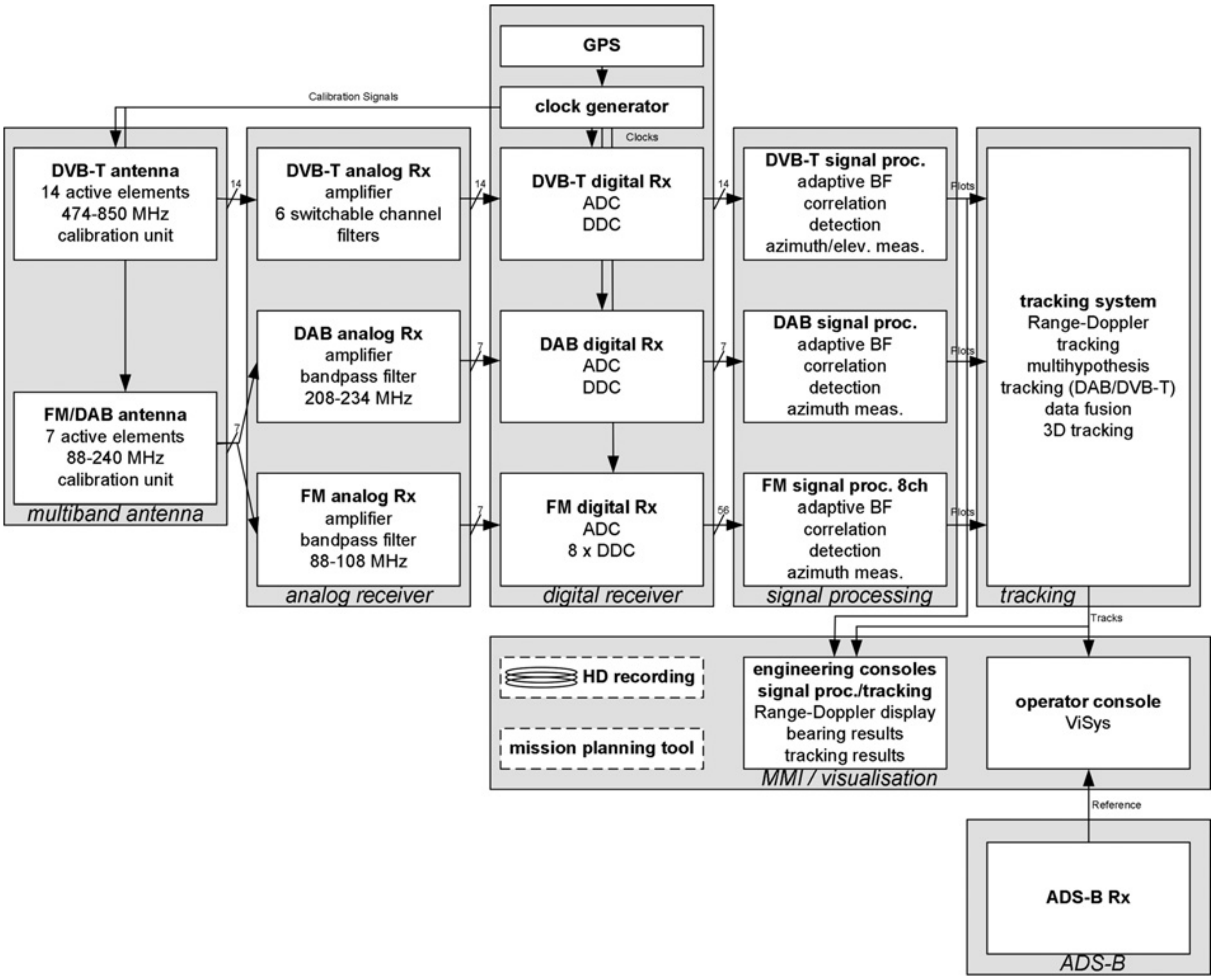

Fig. 3 *PR system architecture*

rate as well as the track behaviour including track attributes as heading and speed. Fig. 4 shows the combined information on ViSys.

The PR is able to provide the ASTERIX data over a TCP/IP data link for the immediate vicinity of the system. For long distance data transfer, a UMTS interface has been implemented to support mobile operation.

2.3 Model-based planning tool

A sophisticated mission planning tool helps the operator to optimise receiver location and to adequately choose the transmitters of opportunity.

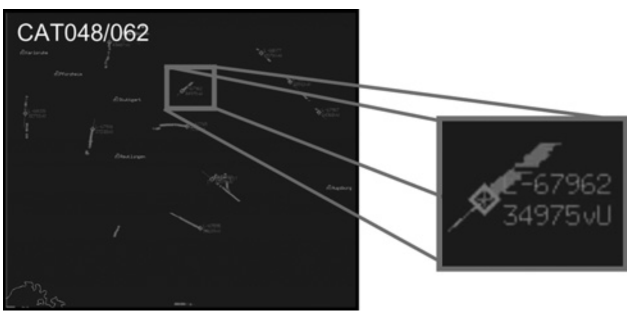

Fig. 4 *Display of PR data in cat.48/62 in parallel*

The tool is based on a performance analysis model which simulates wave propagation, sensor performance and tracking. In order to keep computing time low, the model was realised as a performance model which means it is based on analytic models, such as the radar equation, instead of simulating time signals. It comprises two parallel modes. The coverage mode is used to analyse a specified area of interest. The result is then given by maps, which show track probability and accuracy depending on geographical coordinates. In the trajectory mode, a particular reference trajectory for a given target is considered.

The whole model can be divided into three parts. The first part is called wave propagation model and covers wave propagation and the analogue part of the receiver. Among others it includes models for the antenna diagram of transmitters (see [11]), knife-edge diffraction, atmospheric diffraction and man-made-noise. Digital terrain elevation data of resolution level 1 is used to generate a realistic terrain model. One pixel assumes a size of about 92 m × 92 m near the equator which describes the terrain in adequate preciseness. Information about target signal and noise resulting from the wave propagation model are then passed to the sensor performance model, the second part, which covers signal processing methods (e.g. beamforming, correlation) and detection. Detection probability is calculated by assuming Swerling case 1 for the fluctuation of the RCS. Depending on the chosen mode, the third part of the model can be the tracker performance model in case of coverage analysis. This model calculates track accuracies and probabilities in range/Doppler and Cartesian coordinates based on the detection probability calculated before. If a particular trajectory shall be analysed, the output format of the sensor performance model has to match the real plot data. In this case, the standard tracker is applied.

Transmitters and receiver location are then selected by optimising the output magnitudes of the performance analysis model either of a specified trajectory (track length and accuracy) or an area of interest (track accuracy and probability).

3 Measurement results

3.1 Single-band measurements near Ulm

First, the experimental results for the FM and DVB-T subsystems are presented in the following section. The measurements took place in the area of Ulm, Germany.

Fig. 5 shows the measurement scenario for the FM subsystem. The receiver is positioned in open field in Schwaighofen near Ulm (grey rectangle). Eight analogue radio transmitters (grey dots) situated around the receiver serve as illuminators of opportunity and are processed simultaneously. The distances between the transmitters and the PR receiver are ranging from 11 km to 97 km. Representative detection results are presented for the illuminator ‘Gruenten’. This transmitter is located in the south of the receiver at a distance of 94 km. The transmit power is 100 kW at 104.4 MHz. During the trial, numerous commercial airliners at distances beyond 250 km bistatic range were detected. The referenced flight paths of the aerial targets with a typical height of 10 000 m were tracked by ADS-B.

Fig. 6 depicts the measurement results. The left side shows the referenced bistatic range (light grey lines) over the measurement time (20 min) as well as the measured detections (dark grey dots) of the targets of opportunity. Fusion and tracking of the detections of all eight FM transmitters lead to a reliable and time consistent air picture with tracks up to 160 km distance with respect to the receiver position. This is shown in the right part of the figure with system tracks marked in dark grey and referenced ADS-B data marked in light grey (see also [10]). With the ADS-B data as reference, the completeness of the air picture can be judged. Position accuracy of the system tracks is 500 m in lateral and vertical axis’ for the above-mentioned tracks in ranges up to 160 km and target heights of approximately 10 000 m. Additional fusion of DAB/DVB-T data is expected to increase the accuracy in the near range up to 50 km significantly.

With the DVB-T subsystem, additional trials with ground targets (vehicles) were performed. A van equipped with GPS driving on a test area was used as a cooperative target for the DVB-T measurements. The PR receiver was again located in Schwaighofen near Ulm. The DVB-T illuminator ‘Ermingen’ is located in the west of the receiver at a

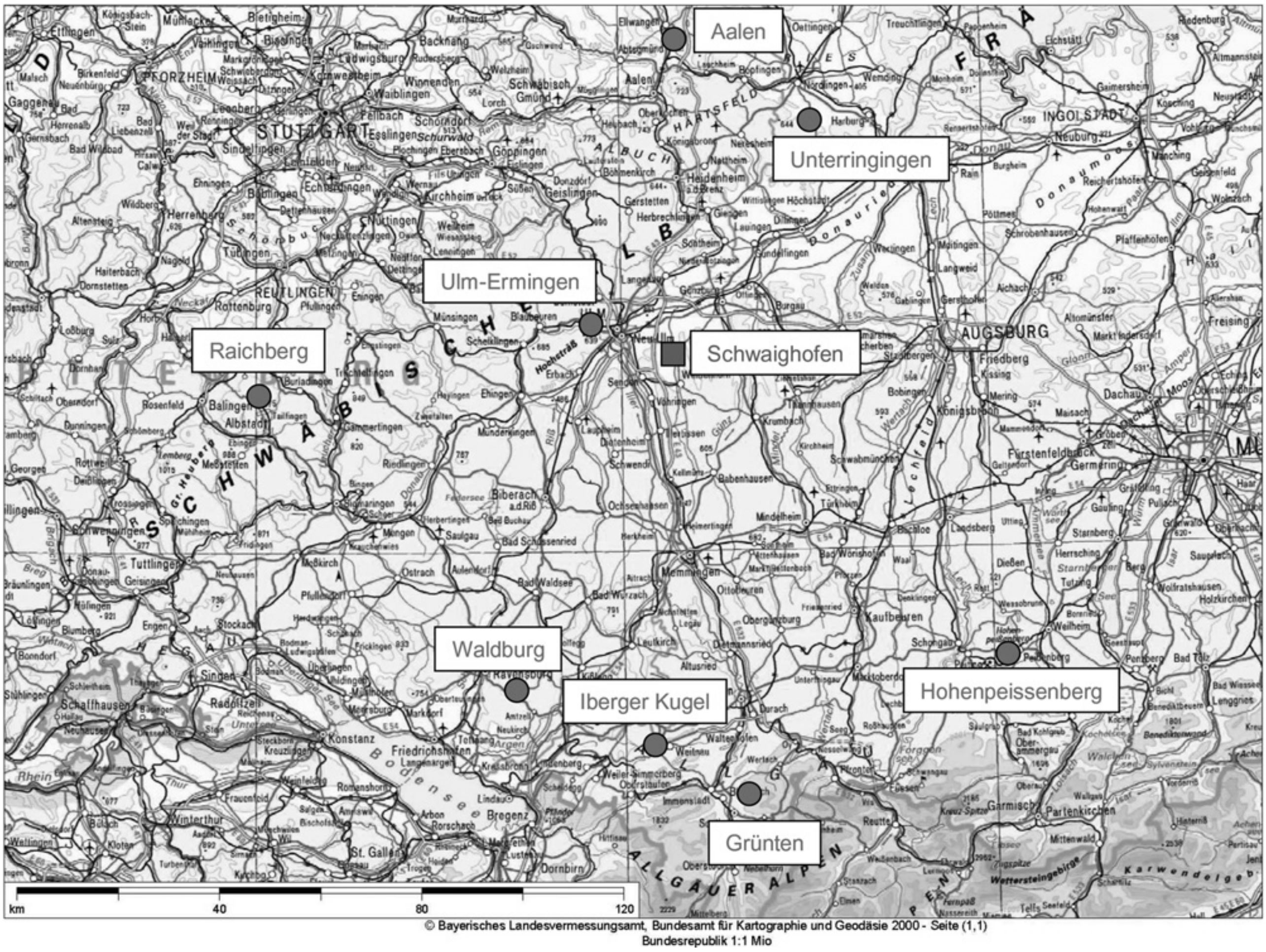

Fig. 5 *Map of trials area*

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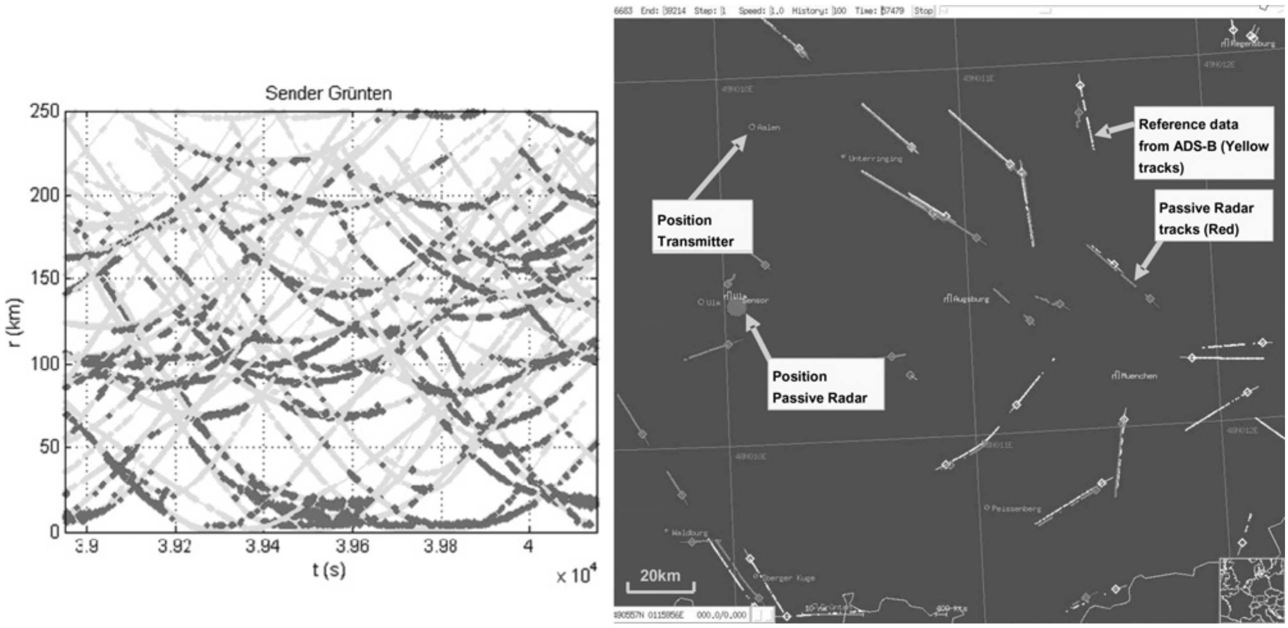

Fig. 6 *Single FM transmitter-based target detection (left) and FM tracks visualised on ViSys (right)*

distance of 11 km. The transmit power is 50 kW at 626 MHz. The next transmitter operating at 626 MHz is located in Raichberg at 78 km distance. Since only 4 km bistatic range is processed, a single illuminator scenario can be assumed. Fig. 7 shows the referenced bistatic range of the van (grey curve) as well as the detections on the target (grey circles). Sensor blind areas (near range <80 m, zero Doppler) are marked black. Reliable detections are seen up to 3 km bistatic range.

3.2 Single-band measurements at Lake Constance

The Lake Constance trials took place in July 2011 at Friedrichshafen, Germany, in the context of a common measurement campaign with Fraunhofer FHR (see [12]). Fig. 8 shows the measurement scenario including sensor position (black dot), target trajectory (grey curve) and all transmitter positions including their normalised azimuth antenna diagram of all waveforms FM, DAB and DVB-T. The target was a low altitude airship equipped with a GPS

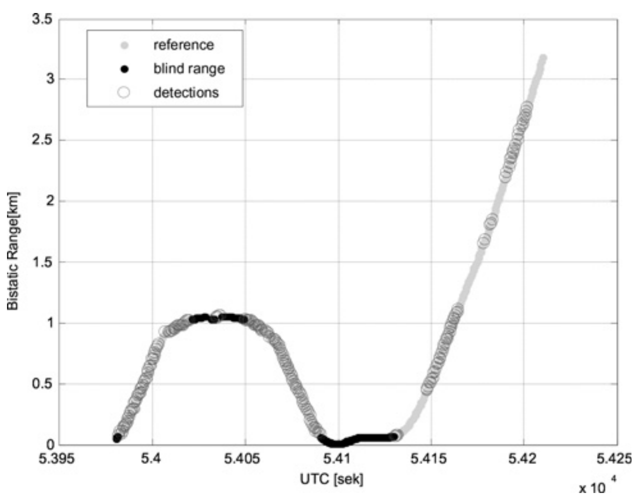

Fig. 7 *Single DVB-T transmitter ground target detection*

reference system. The duration of the trial was 38 min. The direct path distances between transmitter and receiver are ranging from 9 km for the DAB transmitter Konstanz to 94 km for the FM/DAB transmitter Rigi in Switzerland. Transmit power spans from 27 dBW for small DAB transmitters up to 50 dBW for strong FM and DVB-T illuminators.

The detections given by the single systems FM (left), DAB (middle) and DVB-T (right) are shown in Fig. 9. For the FM-system, eight appropriate transmitters of opportunity can be chosen independently from each other within the complete FM band. Fig. 9 (left) shows exemplarily for the transmitter Feldberg (89.8 MHz) the referenced bistatic range (grey curve), sensor blind areas (marked black) and the detections made by the system (grey circles). The figure depicts that the airship target is detected regularly during the whole trial. Plot data analysis of the other simultaneously processed FM transmitters reveals that 7 out of 8 FM transmitters detected the target continuously.

For DAB measurements, transmitters from the Switzerland side of the Lake Constance area were used. The whole German-speaking Switzerland is covered by one DAB SFN at 227.36 MHz which contains more than 100 single transmitter stations. Fig. 9 (middle) shows exemplarily the results for the 19 closest transmitters of the scenario. The colours have been chosen according to the above shown measurement data (reference track as grey curve, sensor blind areas in black and detections of the different illuminators as circles). It can be seen that approx. 10 of them contributed to target detections regularly.

The DVB-T SFN at 482 MHz contains four single transmitter stations in total. According to the instantaneously processed bistatic range up to 38 km, only two of them (Ravensburg as reference and Donaueschingen with its DS at 36 km bistatic range) have to be considered. From Fig. 9 (right side) it can be seen that the target (reference track as grey curve, sensor blind areas in black) was illuminated by the reference transmitter almost all the time (grey circles). No detections were made at the beginning and at the end of the trial when the target had

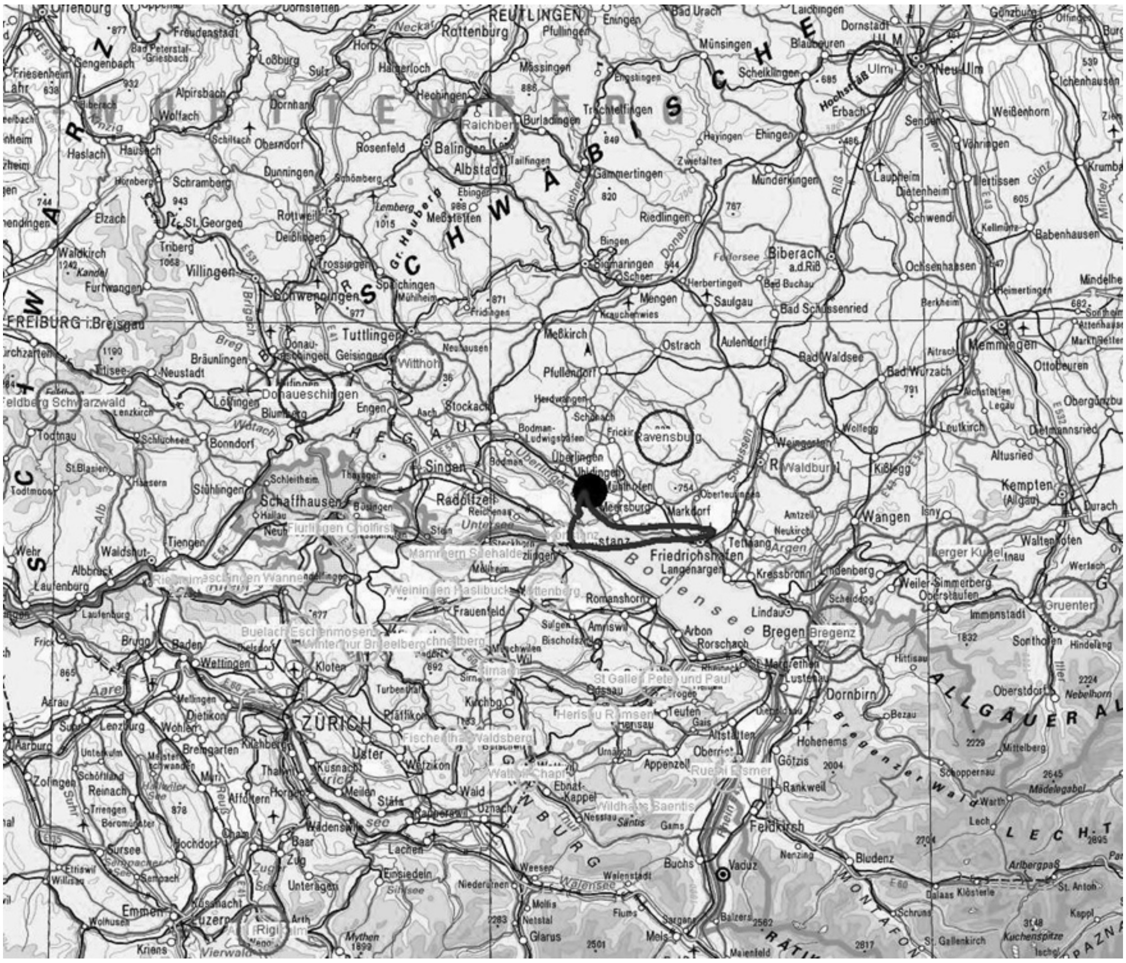

Fig. 8 *Lake Constance trials area*

not reached its operational height which is approx. 400 m AGL. The second transmitter Donaueschingen (grey circles at approx. 36 km) could only add sparse detections in the range between 36 km (DS) and 38 km (maximum processed bistatic range). In total, 19 transmitters (7 FM transmitters, 10 DAB transmitters and 2 DVB-T transmitters) were contributing detections to the trial.

3.3 Multi-band measurements

In a measurement, which took place in Mitterteich (Germany) in spring 2013, first results regarding the fusion of the three single systems could be achieved. In this scenario, eight FM illuminators, approx. five DAB and three DVB-T illuminators contributed.

The target was following a horizontal loop, changing the height in each round. The whole trajectory is shown in the left part of Fig. 10. The reference trajectory is marked in light grey, while different colours of the dots show by which subsystem the existing track has been updated. In the right side of the figure an extract of the distance of the target with respect to the receiver over time is plotted. The colours have been chosen alike. For this configuration an accuracy of 30 m could be reached.

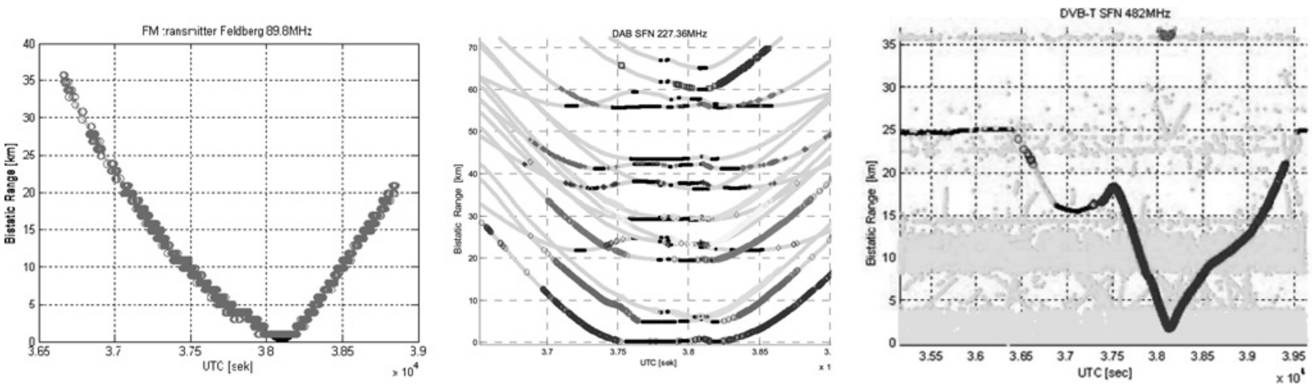

Fig. 9 *FM-based detections of airship target (left) and multi-illuminator detections from DAB SFN transmitters (middle) and DVB-T based detections (right)*

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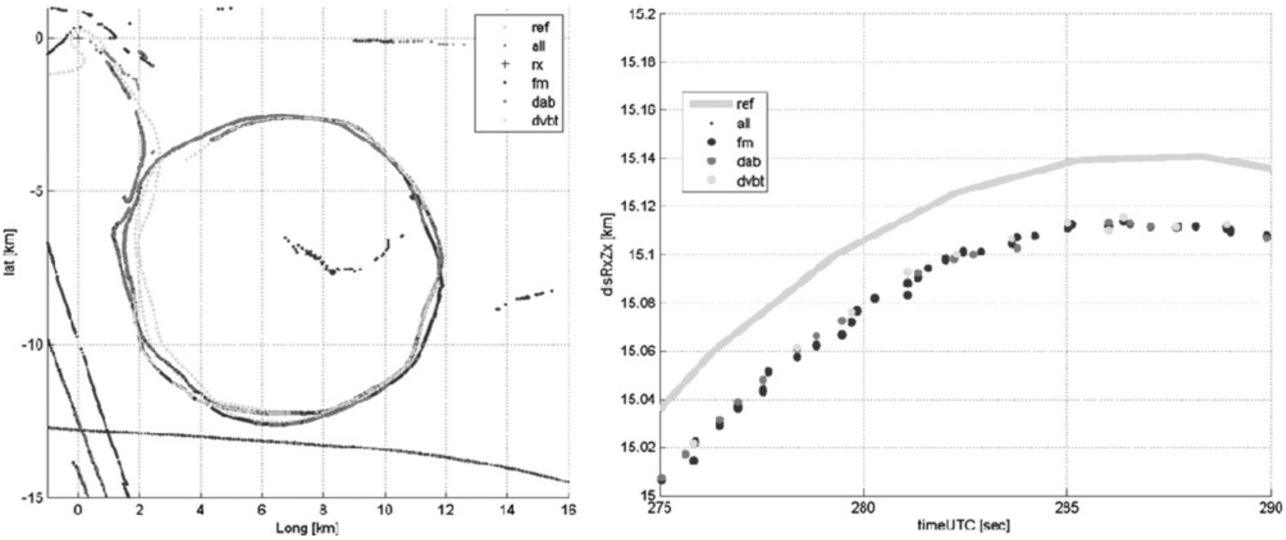

Fig. 10 *Multi-band measurement realised in spring 2013 – overview (left) and range measurement (right)*

Both figures show that each of the subsystems is contributing comparably to the target localisation. The combination leads to the high range accuracy of 30 m, which cannot be reached with FM-illumination only.

3.4 Sensor cluster experiments

In 2012, a second stationary PR system operating in the FM-band was set up on the Cassidian premises in Ulm

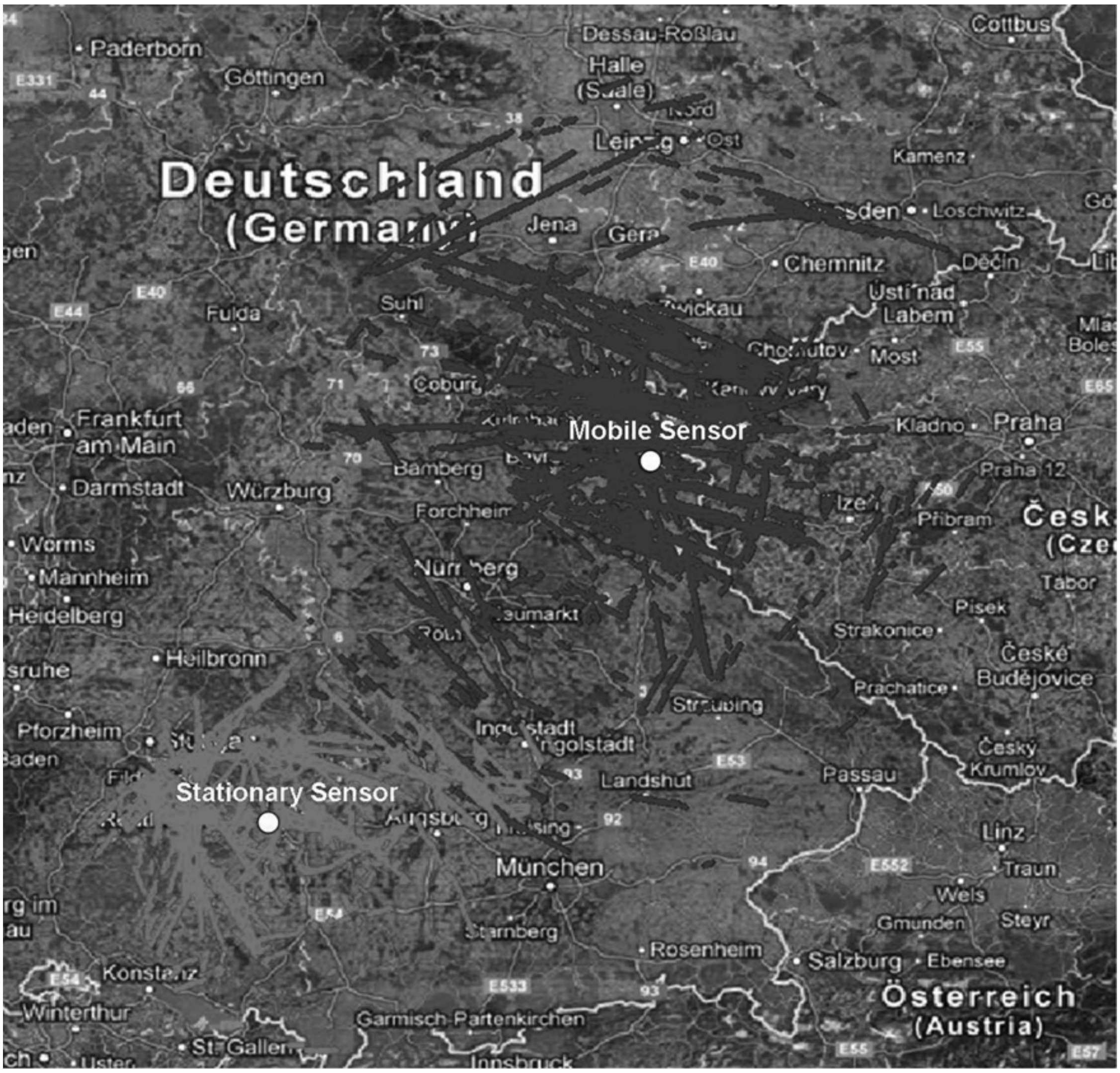

Fig. 11 *Independent tracking results of both sensors mapped together*

(Germany). It was realised as a nearly one-to-one copy of the FM part of the mobile van. According to the multi-band equivalent, the antenna was designed and manufactured in a product-oriented way.

Independent tracking results of both sensors during the same time period are shown in Fig. 11. The mobile PR van (dark grey tracks) was located in Mitterteich (Germany) with a distance of approx. 240 km from the position of the stationary system (light grey tracks) in Ulm. As can be seen, the two sensors are already covering a large part of Germany and the tracking results of both single sensors are overlapping in a certain area. Fusion of the detections of both sensors already inside the MHT would additionally enhance the system coverage and tracking accuracy performance due to further TDoA ellipsoids contributing to the localisation process.

4 Conclusions and outlook

In this paper, an overview of a near-production stage multi-band mobile PR system is given. It is shown that the combination of FM, DAB and DVB-T bands leads to a reliable overall air picture and that PR applications for naval and ground scenarios are also feasible. Based on this prototype system, future development effort is directed towards the fusion of data from several spatially distributed sensors, that is, a sensor cluster, in a central MHT. This increases the overall coverage area and potentially further enhances the localisation accuracy and target track probabilities. By means of sensor cluster measurements, the level of enhancement can be analysed and information regarding adequate sensor placement can be gathered. These measurements will start in summer 2013.

5 Acknowledgments

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