2016/2500M-0059

ISSN 1797-3457 (verkkojulkaisu)
ISBN (PDF) 978-951-25-2855-4

TIIVISTELMÄRAPORTTI (SUMMARY REPORT)

Kaukaistenilmavalvontakohteiden Doppler-seuranta (Doppler-based monitoring of distant air surveillance targets)

Tuomo Kauranne (tuomo.kauranne@lut.fi, 0405300622)
Piotr Ptak, Miika Tolonen, Juha Hartikka, Mauno Ritola – Lappeenrannan teknillinen yliopisto, Adam Ludvig, Azra Tayebi, Matti Korhonen – Arbonaut Oy

Tiivistelmä: Hankkeen tavoitteena on tutkia DX-kuuntelussa selvästi havaittavien lentokoneiden Doppler-kaikujen käyttöä operatiivisen ilmatilannekuvan muodostamiseen käyttäen hyväksi internet-tai tietoliikenneverkkopohjaista havaitsijoiden välistä tiedonvaihtoa ja hajautettua laskentaa.

Tutkittavan menetelmän erityispiirteinä ovat:
- Kaukaisten ilma- ja avaruuskohteiden seuranta
- Passiivinen, vikasietoinen ja kustannustehokas toteuttamistapa
- Sotilaallisen valvonnan ja siviili-ilmailun turvallisuuden yhteiskäyttö

1 Introduction

The most recent history of aviation disasters shows that there is a need for alternative tracking methods. Technology that is currently used, such as ADS-B, automatically assumes cooperation between an airborne object and ground based receiving station. This assumption can lead to the situations in which on-board reporting system is malfunctioning and the surveillance system is unaware of the location or condition of the aircraft.

The system that our group is developing is based on multi-static radar configuration which is a non-cooperative surveillance system. The advantage of the system over conventional primary and secondary radar is the fact that it does not expect any cooperation by the target. Most aircraft are not aware that they are being tracked because the system is purely passive and uses illuminators of opportunity only.

The research group consisted of eight people, among which there were specialists, researchers and programmers. The operators of the receiving station were collaborating voluntarily because of their active interest in the topic.

We would like to apologize for extending the number of pages to 13, however fitting all the material was not possible with suggested maximum of 10 pages.

2 Research objectives and accomplishment plan

The ultimate goal of the project was to proceed with developing an alternative system for tracking non-cooperative target (aircraft) (NCT) based on the VHF Doppler phenomenon by exploiting transmitters of opportunity and radio receivers. The objectives of the projects in order of importance were to:

- check for highly maneuvering objects (HMO) like military aircraft and recognize if any of them were visible in a form of Doppler signature;

- test tracking system of NCT by exploiting three receiving nodes and one transmitter; check accuracy of estimated object trajectory with use of reference data based on ADS-B protocol S data information retrieved from flightradar24.com portal.
- create coverage maps indicating regions for which receiving antennas can spot an airborne object by means of Doppler signature;
- check for planned launches of high flying objects (HFO) from Plesetsk Kosmodrom and recognize if any of them were visible in a form of Doppler signature;

All of the aforementioned goals were accomplished by the research group by the middle of November, 2016. Beside the planned objectives the group was able to research or construct the following:

- the research group gained a permission to install a receiving station at the military base located in Taipalsaari Sarviniemi;
- test affordable receiver setups;
- run recording trials of Radio Signal Data (RSD) for two reception bands: VHF, HF;
- erect new antenna(s) of different types at various locations in Finland;
- build up a communication protocol to be used between receiving nodes and the server;
- set up a repository of retrieved data which can be accessed by every member of the research team; the data consist of two types: RSD and FR24;

3 Materials and methods

The section explains the phenomenology of the Doppler effect in a bi-static configuration of radar as the key feature on which the discussed project is based on. Moreover the following is briefly discussed: acquisition, content and preprocessing of the RSD and FR24; geographical situation of the receiving and transmitting nodes; the method for Doppler signature extraction from within the VHF spectrogram; basics of tracking technique; construction of coverage maps; new equipment setup for receiving node with Raspberry Pi and USB radio stick.

Moreover, the basic configuration of receiving station is presented.

All the following methods are provided with a graphical user interface constructed in Matlab environment.

3.1 Doppler effect in bistatic radar configuration

Definition of the bi-static radar describes it as one with receiving (R) and transmitting (T) antennas at different locations, see Figure 1.

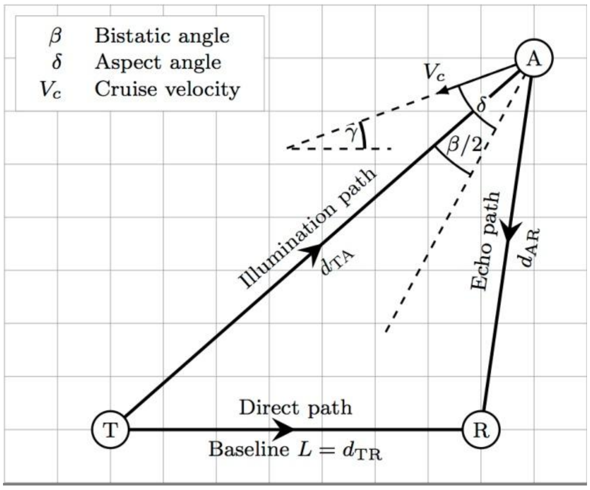


Figure 1: Bistatic radar configuration schema

As the object (A) moves with respect to the transmitter and the receiver, the reflected transmitted signal changes its frequency and is retrieved in a form of a Doppler curve (signature). Both direct path and echo path originated signals are retrieved with receiving nodes in order to estimate the object's trajectory.

3.2 Acquisition, content and preprocessing of the RSD and FR24

The preliminary stage of preprocessing of RSD includes digitalization of the analog signal and filtering. Then the signal is recorded in a form of an audio file and streamed to the analyzing center for further preprocessing. At the analyzing center the audio data is transformed into a spectrogram form by using the Short-Time Fourier Transform. This representation of the acquired signal enables the system to search for Doppler curves, see Figure 2.

In order to validate the tracking accuracy yet additional data had to be acquired. This time the signal, in digital form, comes from a Cooperative Target (CT) tracking system, that is ADS-B. Among many parameters within the protocol the most interesting are location of the airborne object (latitude, longitude, altitude), time stamp, ICAO of the object, and origin and destination airports. As the RSD data was streamed to the analyzing center the FR24 data was simultaneously retrieved from the portal to sustain synchronization of those two data types, see Figure 2.

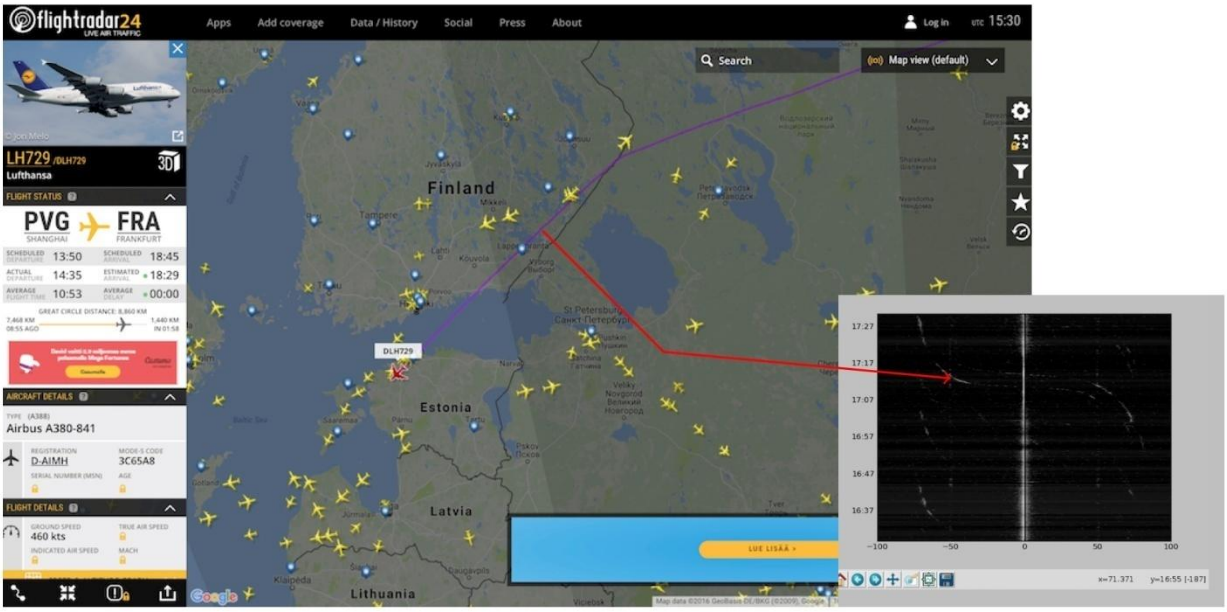


Figure 2: Snapshot from flightradar.24 portal together with spectrogram of RSD consisting of Doppler curve being an effect of the moving aircraft (aircraft trajectory highlighted with purple solid line)

3.3 Geographical location of the transmitters and receiving nodes

Three receiving nodes were used during the project with a total of six antennas of four different types. For the tracking experiment three of those antennas were used to retrieve the RSD and checked the tracking capabilities of the receivers with use of transmitters of opportunity such as radio stations or TV stations. The locations of the receivers and transmitters are shown in Figure 3.

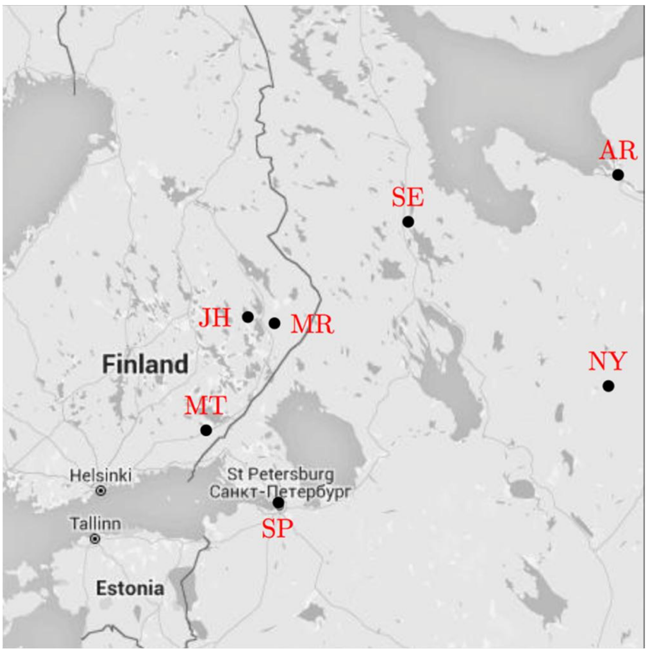


Figure 3: Geographical location of the receiving and transmitting nodes

3.4 Doppler signature extraction method

The method for the extraction discussed and used in the project is partially based on the Viterbi method. However some novel blocks dedicated to the time-frequency analysis of Doppler signature were introduced. The transformed signal in form of one row of spectrogram is fed as an input to the algorithm. The method is built of blocks which guarantee instantaneous processing of the input data. In fact the method has a 0.5s time response between the moments of acquisition and extraction, which is dictated by STFT's hop size between consecutive rows of data. For more detail, refer to[4]. An example of extraction is presented in Figure 4.

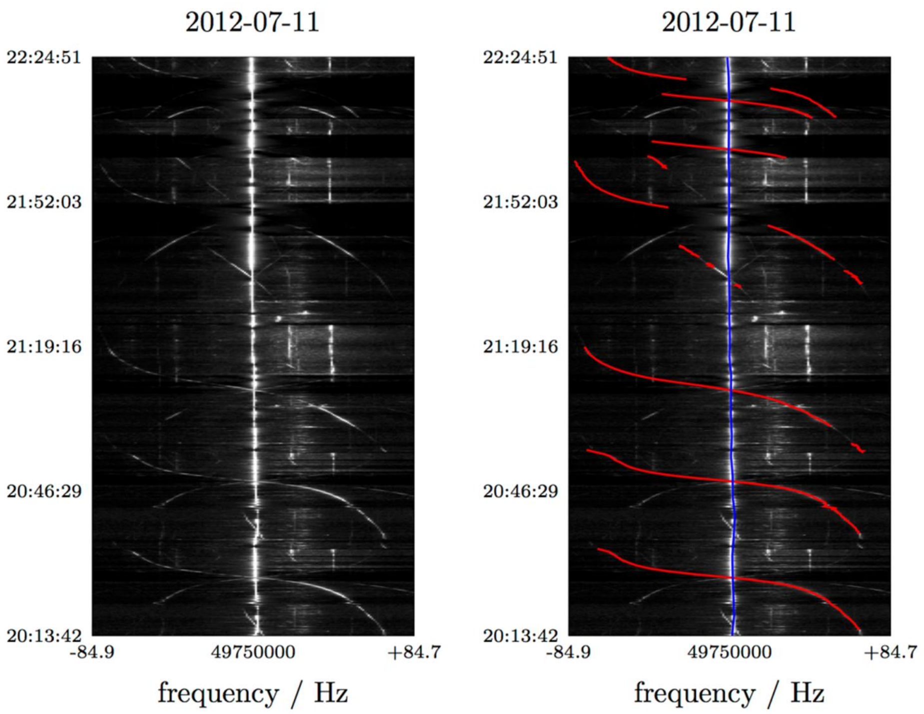


Figure 4: Example of performance of the extraction method. Left: spectrogram with visible Doppler curves, right: spectrogram with extracted features.

3.5 Tracking technique

The following conditions must be fulfilled in order to apply the tracking method: the Doppler curve must be detectible by the extraction method; Continuously detectible Doppler curves when using different receiving stations; The curves must intersect with the carrier frequency;

The methodology is based on an inverse problem solving approach, that is,with each iteration a synthetic trajectory is produced based on which the Doppler shift is calculated. Then the residuals between the synthetic and extracted Doppler curves are calculated and designated as a cost function. The method iteratively searches for the minimum cost function which corresponds to the optimal trajectory estimation. This is merely a brief explanation of the method, for more detail please refer to [5].

3.6 Constructing coverage maps

The purpose of studying this issue was to find out how large is the observable region when we use each transmitter and receiver pair. There were five antennas to be checked using four transmitters located in adjoining territory of Russian Federation. As the purpose of this experiment was not yet to track the aircraft in real time, the ADS-B originated synthetic Doppler curves were compared (coupled) with extracted Doppler curves. By comparing those two sets a fine estimation of coverage area could be performed. The coverage maps consist of all of the observed flights, so the histogram of passing aircraft types (ICAO) can be attached.

By using the spotted trajectories and applying an appropriate algorithm on them, the borders of observable territory have been drawn and calculated. Taking an average cruising altitude to be 10km and an actual height over ground for each antenna the horizon of the line of sight was calculated.

3.7 Raspberry Pi and radio stick

As the project evolved the research team started to consider finding new solutions for receiving node equipment. The need for this was dictated by the fact that common equipment used at the receiver is expensive andis often accessible in black-box form only. Additionally a set of equipment that has many components can be unreliable. Therefore the search for alternatives was started.

To fulfill all the parameters for an optimal solution the research team started researching Raspberry Pi and stick radio as the most promising one. For this purpose a new antenna was erected on September 28, 2016 on the roof of the Lappeenranta University of Technology building. The feed from the antenna was attached to the radio stick for signal digitalization. Then the operator of the receiver was able to develop software that completely fulfilled the needs of the preprocessing stage. Such a signal could then be sent directly from RP to the analyzing center. The node was operational by the middle of October.

3.8 Receiving station

The basic configuration of the receiving stations consist of the following equipment:

- Mast for antenna(s), often of tens of meters high, or radio mast, 30m to 500m;
- Receiving antenna. The following VHF antennas were used:
    - Q8E - eight element quad;
    - D4E - four element dipole;
    - Y6E - six element Yagi;
    - Y4E - four element Yagi;
- Software Defined Radio (SDR) or stick radio for digitalization of analog signal or dedicated equipment such as FT-100D;
- Computer unit for visualization of incoming signal in the form of a waterfall-spectrogram.

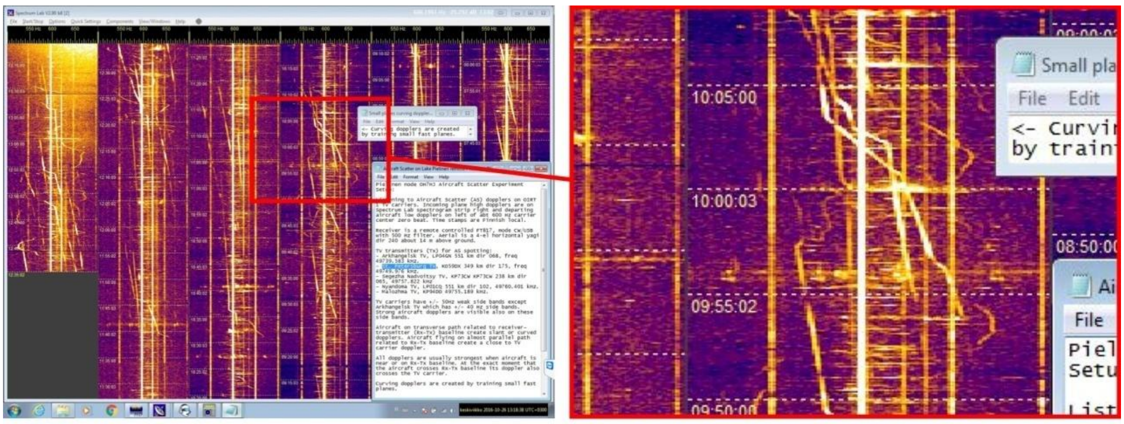
4 Results and discussion

4.1 Highly Maneuvering Objects

Spotting HMO was of the highest importance among the goals of the project. Therefore the data was continuously surveyed for the whole time the project lasted for potential presence of HMO on spectrograms. Two antennas and four transmitters were used for this experiment, receivers at JH and MT locations and transmitters at SP, SE, NY and Malozhma.

The surveying resulted in many situations where HMO were identified at both receivers. Because the HMO are not equipped with – or using –an ADS-B system the validation could not be performed at that stage. But the very fact that such HMO were not visible with FR24 partially validates the presence of such aircraft, taken that such undetectable aircraft are not very often visible on RSD either.

Two areas where the HMO were active were estimated - North Pielinen and lake Ladoga. The presence at the second location was validated by retrieved radio communication-conversation between HMO and ground station receiver. In both cases the jet activity was for training purposes. The presence of Doppler curves is shown in Figure 5as a highly non-stationary hairlines passing through a strong carrier.

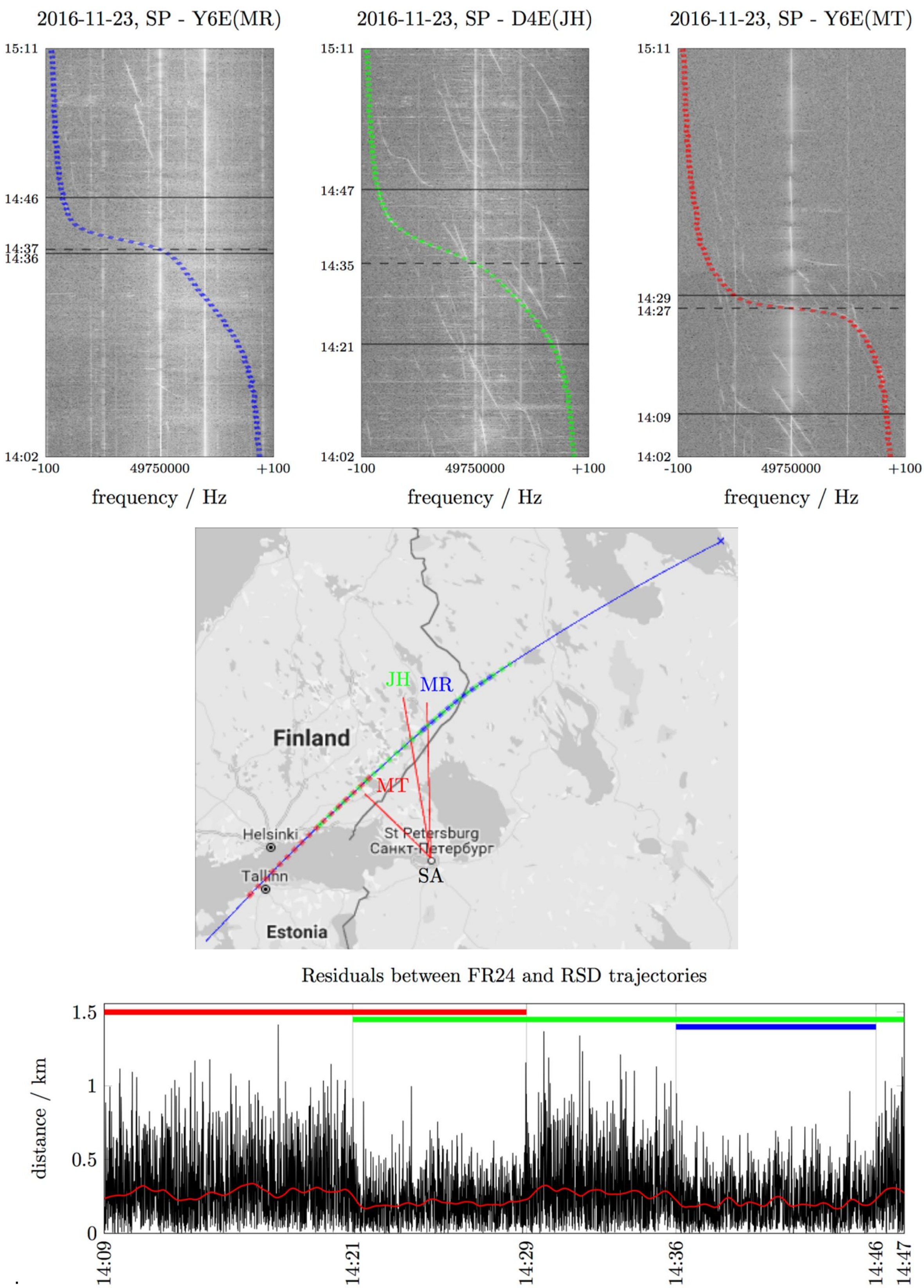


(a) (b)

Figure 5: a) Spectrogram of RSD and b) its magnification onto the Doppler curves of HMO.

4.2 Tracking system of NCT

The purpose of this part is to demonstrate how accurate the Doppler-tracking method of aircraft is. For that experiment three receiving stations were used – JH, MR and MT. Each of those three was tuned to record signal coming from SP transmitter. One particular flight was taken under consideration having both FR24 reference data and visible RSD Doppler curves. Firstly the curves were extracted with use of previously presented extraction method, one curve for each receiving node. After that the fitting of optimal trajectory started with use of inverse problem solving approach. Figure 6 consist of three parts: spectrograms with visible extracted parts limited by upper and lower time frames (black solid lines) when the Doppler was visible; Map with the whole trajectory from FR24 (thin blue solid line) and the spectrogram-corresponding parts of estimated trajectory; Finally the graph illustrates residuals between FR24 trajectory and the estimated one;



;

Figure 6: Estimation of trajectory with use of Doppler-tracking method

Residuals between FR24 and RSD trajectories. The average difference between those two sets is 0.25km, but one should notice the precision is higher when aircraft is visible for more than one receiving station simultaneously (see overlapping parts of three lines – red, green and blue). The red curve corresponds to the moving average of the residuals.

4.3 Coverage maps

This section presents settings of the receivers' equipment and transmitter parameters upon which the coverage maps were created, see Table 1.Figure 7 consists of five maps, each for different transmitter-receiver settings. The black solid lines indicate presence of aircraft on RSD, white area underneath the lines represents estimated coverage region, black dashed line corresponds to the horizon for line of sight.

Table 1: Settings for receivers, parameters of transmitters and acquired coverage sizes.

Antenna location	*Antenna type*	*HAG (m)*	*Horizon (km)*	*Transmitter location*	*ERP (kW)*	*Area (km^2)*
JH	Q6E	6	365	NY	5	22625
JH	D4E	14	370	SP	149	138776
JH	Y6E	20	372	AR	5	17367
MR	Y6E	10	368	NY	5	71108
MR	Y4E	10	368	SP	149	14415

4.4 HFO at Plesetsk Kosmodrom

As in the case of HMO, spotting HFO was another prioritized goal of this project and its realisation started in February. One team member was especially assigned to check for planned launches at the Kosmodrom and checking for those which are not officially announced. Table 2 presents information on launches from Plesetsk.

Table 2: Overview of the launches taken from PlesetskKosmodrom in 2016.

Date	*Configuration*	*Cargo*
June 4	Rockot	GEO-IK 2
May 29	Soyuz-2.1b	Glonass M
March 24	Soyuz-2.1a	Bars-M
February 16	Rockot	Sentinel 3A
February 7	Soyuz-2.1b	Glonass M

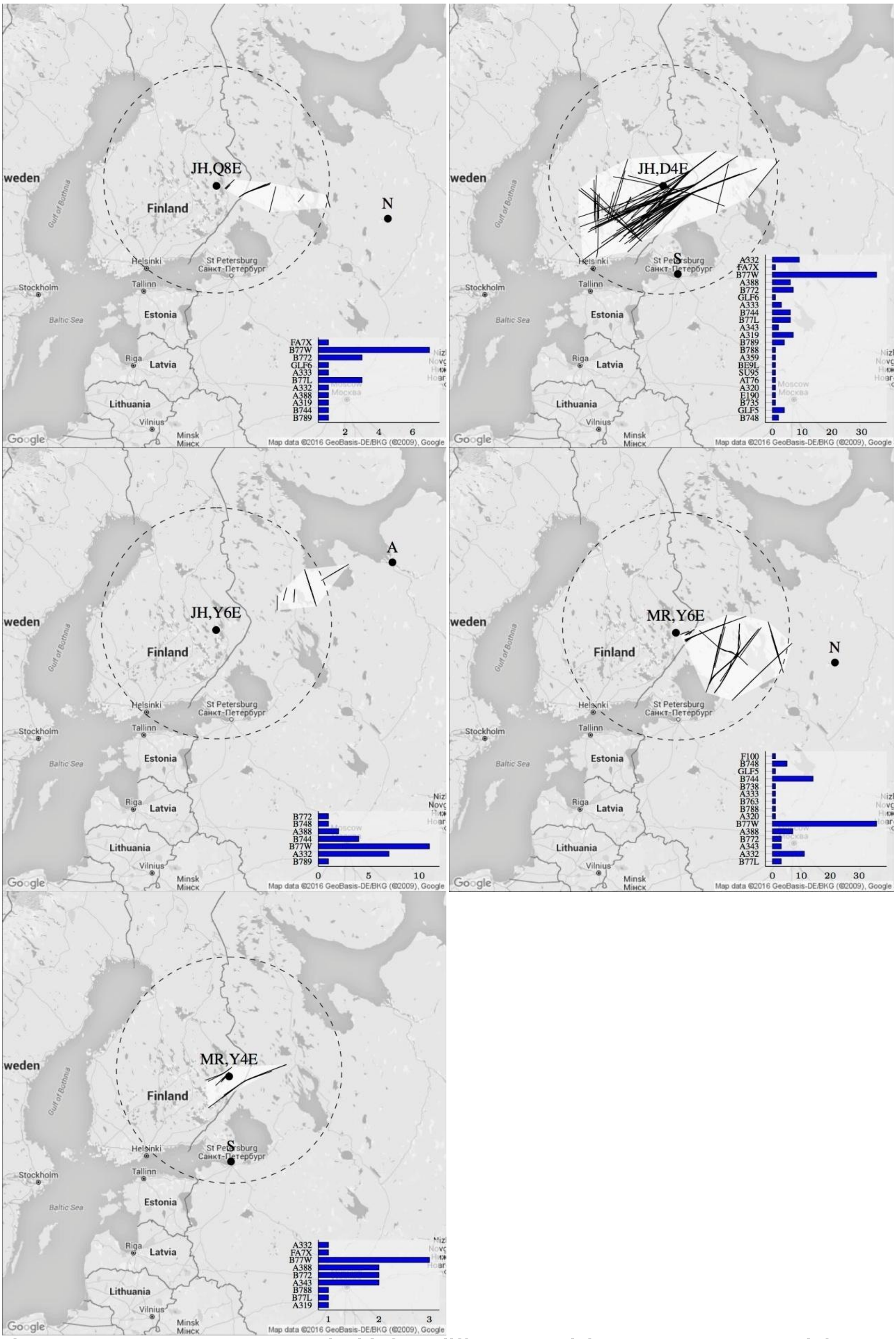


Figure 7: Coverage maps created with four different receiving antenna types and three transmitters. The histogram of appearance of various types of aircraft (ICAO) attached.

The group started from a decision on which station (transmitter) to use so that launches from Plesetsk Kosmodrom could be visible. The location must fulfil the requirement of being behind Plesetsk with respect to the location of the three receiving stations. The distance from Kosmodrom to the potential transmitter must have been balanced, not too short because it will limit the time of rocket being ”visible”, not too long to not substantially weaken the scattered signal. The distance between Joensuu and Plesetsk is 537km therefore the receivers were out of line of sight in this situation, so dealing with bouncing path of propagation was unavoidable in the case of VHF.

The most promising transmitting station was located in Arkhangelsk. However the continuous observations of HFO did not result in the detection of any RSD Doppler signature.

5 Conclusions

By and large the project attained its goals and demonstrated the feasibility of long distance air surveillance by the proposed concept. Although high altitude ballistic objects were not detected, both military and civilian flights were detected and the latter ones also tracked and validated with ADS-B data. The coverage area of the system also proved to be rather wide, reaching to over 500 km distance from receiving stations. An affordable and compact receiver setup was also tested and found working well. We hope to be able to continue this research towards a real-time operational capability with multiple simultaneous receivers and transmitters coupled together.

6 Scientific publishing and other reports produced by the research project

Throughout the years the research group published as journal papers and conference contributions. Among them three items ([2],[3],[4]) were published this year.

[1] Ptak, P.;Hartikka, J.;Ritola, M.;& Kauranne, T. (2015). Aircraft classification based on radar cross section of long-range trajectories. *IEEE Transactions on Aerospace and Electronic Systems* , 3099-3106.

[2] Ptak, P.;Hartikka, J.;Ritola, M.;& Kauranne, T. (2016). An alternative way of tracking aircraft based on VHF band Doppler effect phenomenon. *Proceedings of The International Society of Air Safety Investigators, ISASI 2016 Conference.*Reykjavik.

[3] Ptak, P.;Hartikka, J.;Ritola, M.;Joki, A.;& Kauranne, T. (2016). Forward-scatter Doppler-only Distributed Passive Covert Radar. *NATO SET-231 Specialists' Meeting on "Multi-Band, Multi-Mode, Multi-Static Radar".*Alfeite, Lissabon, Portugal.

[4] Ptak, P.;Hartikka, J.;Ritola, M.;& Kauranne, T. (2016). Instantaneous doppler signature extraction from within a spectrogram image of a VHF band. *IEEE Transactions on Aerospace and Electronic Systems* , 576-589.

[5] Ptak, P.;Hartikka, J.;Ritola, M.;& Kauranne, T. (2014). Long-distance multistatic aircraft tracking with VHF frequency doppler effect. *IEEE Transactions on Aerospace and Electronic Systems* , 2242-2252.

7 Hankkeen seuraajan lausunto raportista

Hanketta on Puolustusvoimien puolelta seurannut ins Ari J Joki, Puolustusvoimien Logistiikkalaitoksen Järjestelmäkeskuksen Ilmajärjestelmäosastolta.

Hankkeessa tutkitut menetelmät täydentävät Puolustusvoimien tekemää muuta ilmavalvontatutkimusta. Tässä tutkimusvaiheessa ja sitä edeltäneessä omarahoitteisessa työssä saatujen tulosten perusteella voidaan pitää mahdollisena, että menetelmistä voi jatkossa kehittää investointikustannuksiltaan edullisen valvontaresurssin. Jatkokehitys olisi kokonaisilmavalvonnan kannalta suotavaa. Jo nämäkin tulokset ovat hyödynnettävissä sekä operaatioanalyysissä että kansainvälisessä tiedonvaihdossa.

Tutkimusryhmä on ollut motivoitunut ja tuottava. Tutkimuksen kapeikkona on matemaattis-luonnontieteellinen resurssi, joka rajoittuu käytännössä yhteen tohtoritason tutkijaan. Tällä yhdellä tutkijalla on kuitenkin saatu johdettua tutkimusryhmän työtä ja tuotettua konkreettisia tuloksia.

Tämä raportti on yhteenveto tutkimuksen aikana syntyneistä tuloksista. Tarkemmin tutkimuksen tuloksista voi lukea luvun 6 viiteluettelon julkaisuista ja artikkeleista. Viitteestä 3 on huomattava että Joki on tähän esitykseen koonnut yhdistelmän tutkimusryhmän muista julkaisuista; Joki ei ole varsinaisesti osallistunut tutkimuksen toteuttamiseen.