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SUMMARY REPORT

Doppler-based real-time monitoring of distant air surveillance targets

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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.

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:

- test tracking system of NCT by exploiting seven receiving nodes and one trans-mitter; check accuracy of estimated object trajectory with use of reference data based on ADS-B protocol S data information retrieved from flightradar24.com portal
- measure performance on cases when aircraft is over the radar horizon
- check for planned launches of high flying objects (HFO) from Plesetsk Kosmo-drom and recognize if any of them were visible in a form of Doppler signature

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 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.

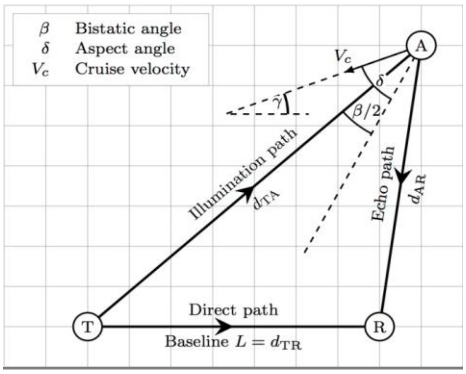


Figure 1: Bistatic radar configuration schema.

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.

3.1. GEOGRAPHICAL LOCATION OF THE TRANSMITTERS AND RECEIVING NODES

Within current year group has been able to extend the receiving network to contain seven nodes. The airspace in and around Eastern Finland up to almost a thousand kilometers away is being monitored. Receiving stations are designed and implemented by authors that collect data 24/7. The locations of the receivers (Antennit) and transmitters (Lähettimet) are show in Figure 2.

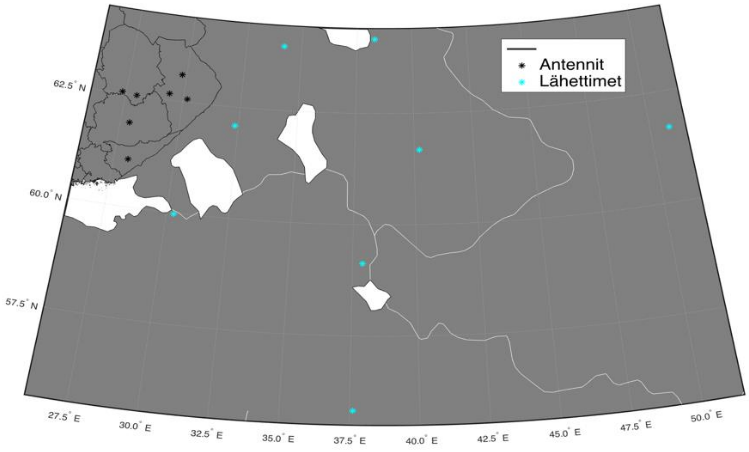


Figure 2: Geographical location of the receiving and transmitting nodes.

3.2. DOPPLER SIGNATURE EXTRACTION METHOD

The extraction method used for the signal is Cell Averaging Constant False Alarm Rate (CA-CFAR) with pre- and post-processor. The preprocessor is a detector which marks signals which are previously found with the CA-CFAR and excludes those from new searches with the CA-CFAR. The purpose of the preprocessor is to decrease gaps within the Dopplers when they are crossing the baseline. Preprocessor also extends the accuracy of the extraction when the signals are close to each other. Post-processor is also responsible for removing constant elements from the extracted signal. Baseline is one of these constant elements and therefore the post-processor records the position of the baseline.

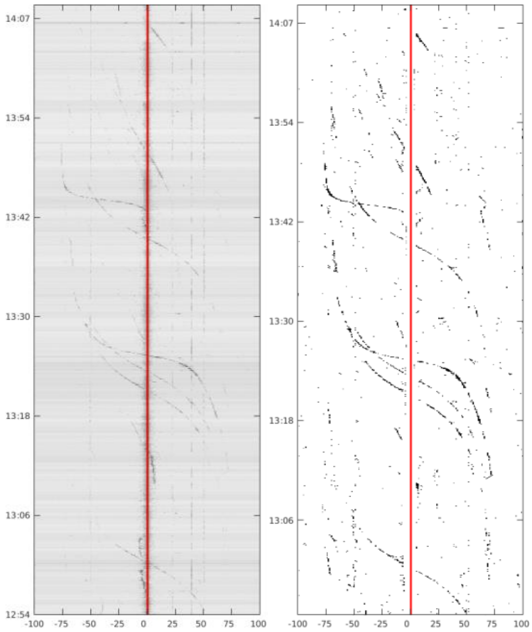


Figure 3: Example of performance of the extraction method. Left: spectrogram with visible Doppler curves, right: spectrogram with extracted features.

3.3. TRACKING TECHNIQUE

The tracking method is based on an inverse approach, which uses extracted Doppler signals to track the location of the aircraft. The tracker is based on the Extented Kalman Filter (EKF), which is a modified version of the Kalman Filter (KF) suitable for nonlinear model equations, where processing in our case is done within Doppler space (Hz) and plane flight data is changed to Doppler space with a nonlinear function. Kalman filter is a filter which can process noisy measurements and combine measurements to the aircraft flight data, but it is at the same time potentially unstable. Instability can be avoided with good initialization of the Kalman model state (aircraft flight data) and with well processed measurements. After initializing the KF with real flight data, the tracker is using Doppler sizes on different receiving stations as its input. The basic nature of KF is least squares fitting, therefore the number of measurements at each time step can vary. EKF is initialized with correct data and it ensures stabilized initialization even if the number of measurements is less than five. After the number of measurements increases, the error estimate from the EKF error covariance matrix is decreasing. Tracking can be extended even over the horizon of the radars, but the error estimate is increasing there substantially and tracking is stopped when the error estimate reaches a limit of 1.5 km.

3.4. RECEIVING STATION

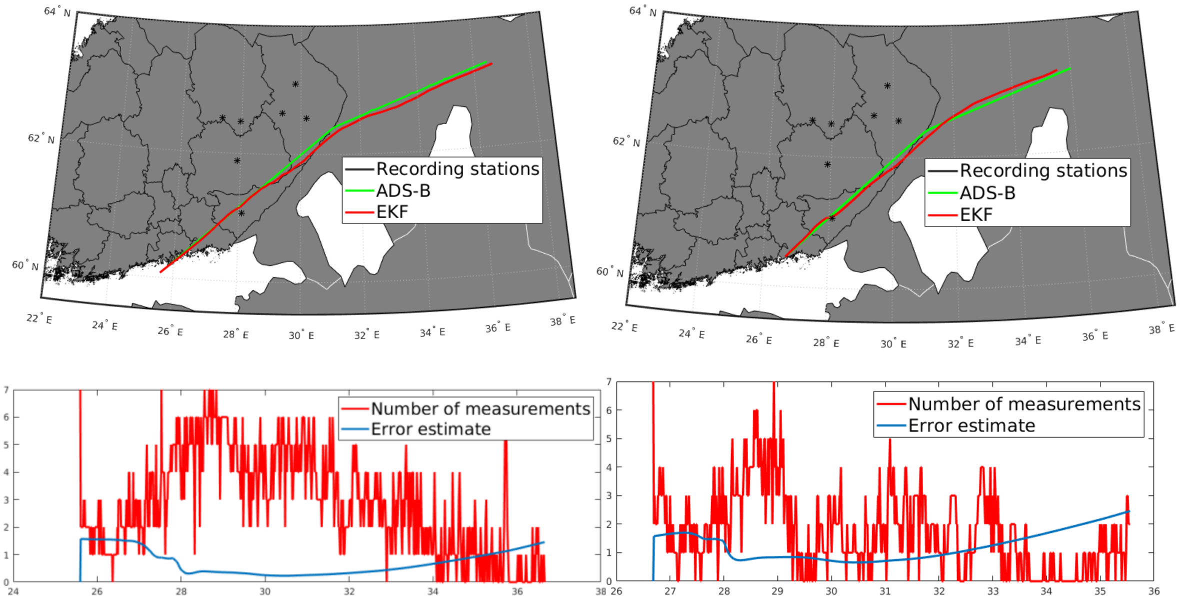
Equipment at the receiving station is Raspberry Pi computer connected with RTL-SDR radio to antenna, which is either a six element yagi antenna or a four element dipole antenna. This setup allows to connect each station to any place where normal electrical power and internet connection is provided. The research group has also prepared a mobile receiving station, which can operate in remote locations fully autonomously. Demand of normal electrical power and internet has been replaced with a battery connected solar panel and mobile internet. The mobile receiving station is not been deployed, but will connected to receiving network within the year 2018 (Figure 4).

Figure 4: Mobile station.

4. Results and discussion

4.1. TRACKING SYSTEM OF NCT

The purpose of this part is to demonstrate how accurate the Doppler-tracking method of aircraft is. For that experiment seven receiving stations were used. Each of these seven was tuned to record the signal coming from SP transmitter. Two flights were taken under consideration having both FR24 reference data and visible RSD Doppler curves. Two flights were recorded with different accuracy, with 1 Hz accuracy and with higher 1/8 Hz accuracy. Assumption was that higher accuracy will extend visible range and tracking will be more accurate. Figure 6a is showing that assumption is correct, extended range is visible with higher number of measurements, which results smaller error estimate. Particular flights were not recorded on same day, which might also have affected the accuracy.

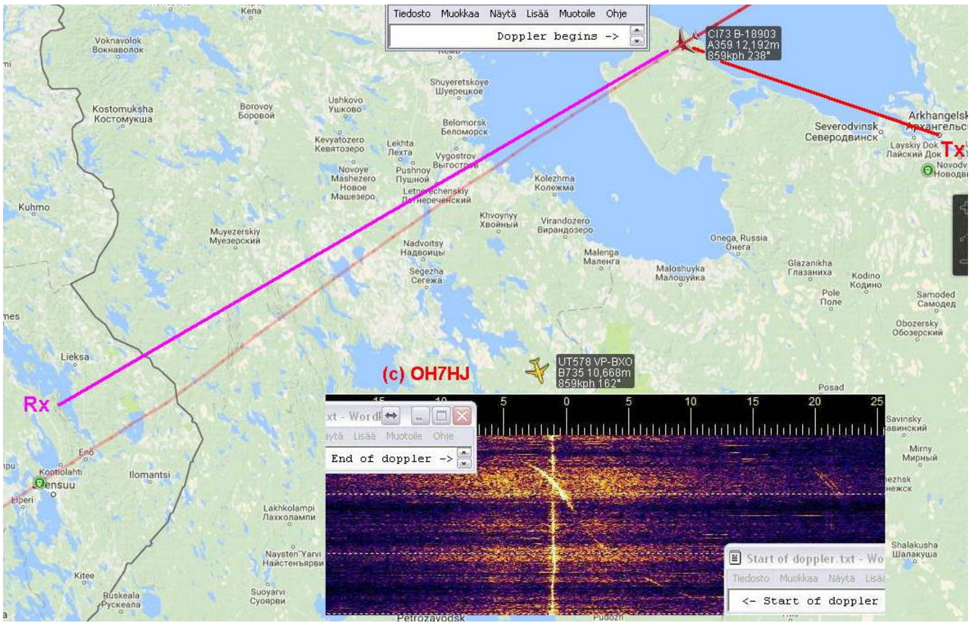


(a) Tracking with 1/8 Hz accuracy (b) Tracking with 1 Hz accuracy

Figure 5: Estimation of trajectory with use of Doppler-tracking method.

4.2. DETECTION DISTANCES

Improvements with receiving equipment has extended reception ranges. With higher 1/8 Hz accuracy aircraft can be seen even from over the horizon. Figure 5 is showing an aircraft which has 458 km distance to the receiving station. Recordings were made on different weather conditions and similar spotting distances where detected.



Doppler begins ->

End of doppler ->

<- Start of doppler

Figure 6: Distant detection from Arkhangelsk TV.

4.3. HIGH FLYING OBJECT

A member of the Sentinel satellite family number 5P was to be taken into orbit on a Rocket launcher from the Plesetsk Cosmodrome in northern Russia on 13 October at 09:27. Our nodes were at that time recording with a wider band, which was containing all the frequencies of the transmitters shown on figure 3. One of the nodes was recording a weak Doppler from that time. That node is equipped with a six element yagi, which is a directional antenna, and is marked with Tarmo sign on figure 6. Doppler signs are marked with red lines to the figure. The figure is showing that there are three different traces, points were traces are separating are matching with rocket phase separation schedule. This does not yet prove that Dopplers which are roughly 500 Hz from Moscow TV frequency baseline are from a Rocket, but projection speed estimate of 3000 m/s=10800km/h makes a Rocket to be the most probable source of the Dopplers.

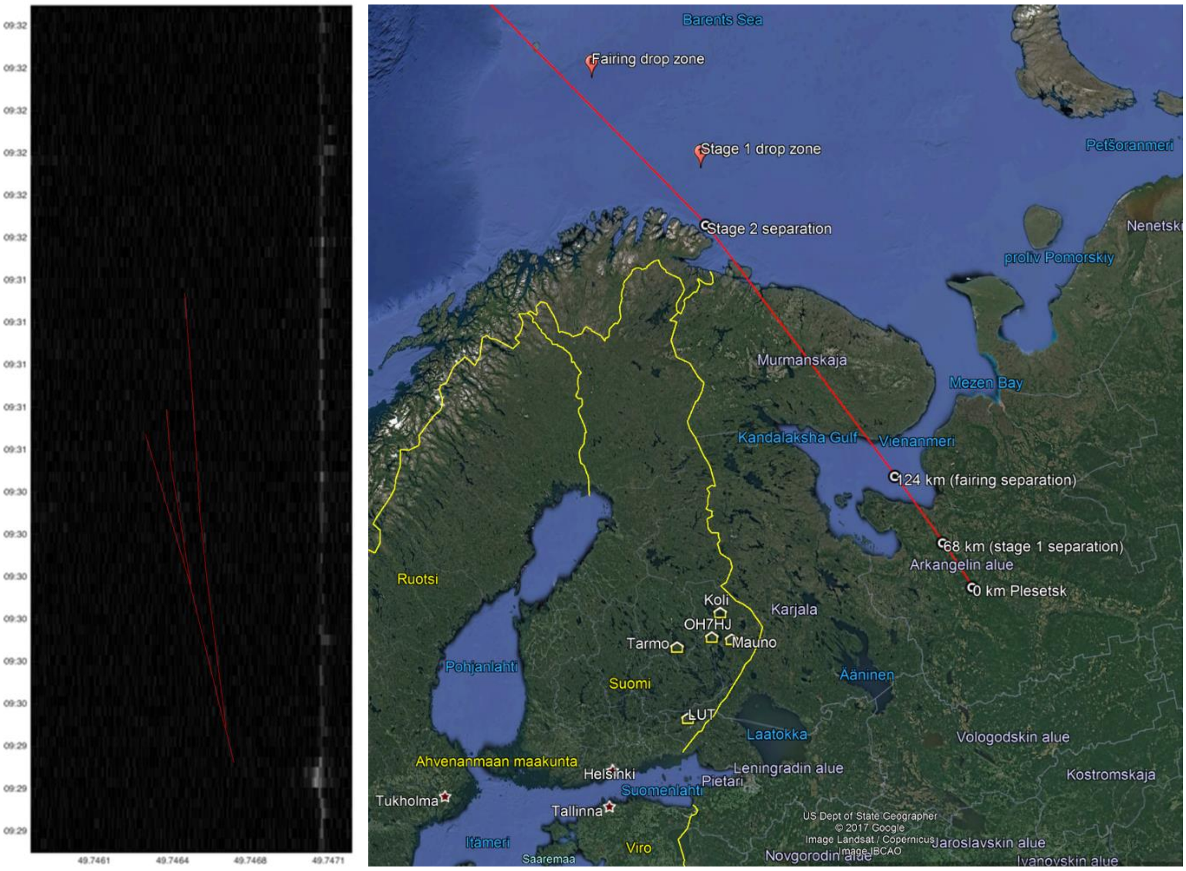


Figure 7: Sentinel 5P launch trajectory and recorded doppler.

5. Conclusions

By and large the project attained its goals and demonstrated the feasibility of long distance air surveillance by the proposed concept. Even high altitude ballistic objects were probably detected although not yet directly positioned. 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 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

[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.

[6] Miika Tolonen, Piotr Ptak, Juha Hartikka, Mauno Ritola, Adam Ludvig, Matti Korhonen, and Tuomo Kauranne. Forward-scatter doppler-only commercial airliner tracking. In The 18th International Radar Symposium IRS 2017, Prague, Czech Republic, Jun 28-30 2017. ISBN ISSN: 2155-5753.