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SUMMARY REPORT

Doppler-based real-time monitoring of distant air surveillance targets (Suomeksi: Kaukaisten ilmavalvontakohteiden reaaliaikainen Doppler-seuranta)

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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:

- Measuring performance when using receivers on wide area.
- Real time observation and tracking of air traffic and high flying ballistic objects.
- Producing operative measurement software
- Automatic initialization of the tracks
- Survey on requirements what would inquire FM-transmitters addition to the system

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 bistatic radar describes it as one with receiving (R) and transmitting (T) antennas at different locations, see Figure 1.

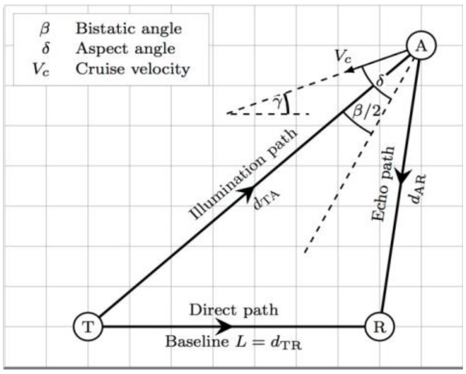

Figure 1: Bistatic radar configuration schema

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. Initialization of the track

Track initialization has been based on ADS-B data in previous versions of the system. The main target for this year was to develop a method to initialize track without external help from ADS-B.

Initialization of the track is a multistep process which contains steps on data processing and steps after the dopplers are extracted from the data. Let us concentrate on steps which are done after the extraction. Initialization starts at the time, when there is confirmation from four stations that they are tracking a doppler. Every station is needing roughly 20 seconds to confirm doppler existence. Four dopplers is the minimum requirement to conduct a look-up table search on the flight data correspondence in doppler space. The look up table contains artificial flight data and corresponding doppler information for 12 million candidate flights. The search result contains 500 best least squares matches to the doppler measurements.

The results can be ambiguous on location and flight direction, but this ambiguity can be removed with information recorded with directional antennas. The remaining part of the result contains multiple results with the same kinematic parameters (flight speed and direction). Points which share kinematic parameters are merged to one representative. This is done to decrease processing time and the points sharing kinematic parameters are geographically close.

History information of the dopplers is used at this point to choose ten best matches from the processed search result. Use of history information can be justified to reason that Doppler shifts are followed before they are recognized and different geographical locations of the receivers are defining different doppler receiving areas to each. Defining the ten best matches from the history data is taking some processing time and while doing this the aircraft has changed its location. This means that we should have new measurements from receivers and we can once again sort these ten best ones with new measurements. Five best ones from those virtual tracks that are matching to the new measurements are then chosen to be virtual targets. These five virtual targets are then processed with the regular tracking technique described below and after a minute of processing the best match to the measurements is chosen to be the tracked target.

3.2. 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

3.3. 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 us 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 deployed since March 2018 (Figure 2).

Figure 2: Mobile station

4. Results and discussion

4.1. Measuring performance when using receivers on wide area

Currently studies on receivers are conducted at individual receiver level. When ADS-B data is used as reference to process data, a single receiver can record 80% of flights which are at the closest to the receiver with maximum distance of 100km and if distance is increased to 200km recording retrieval rate is 75%. We have conducted also tests with 1/8Hz accuracy and with aircraft track whose closest track point to the receiver is less than 200km. In this case the retrieval rate is 90% of the targets. Our original assumption was that higher accuracy will extend visible range and tracking will be more accurate and this results appears to confirm this hypothesis.

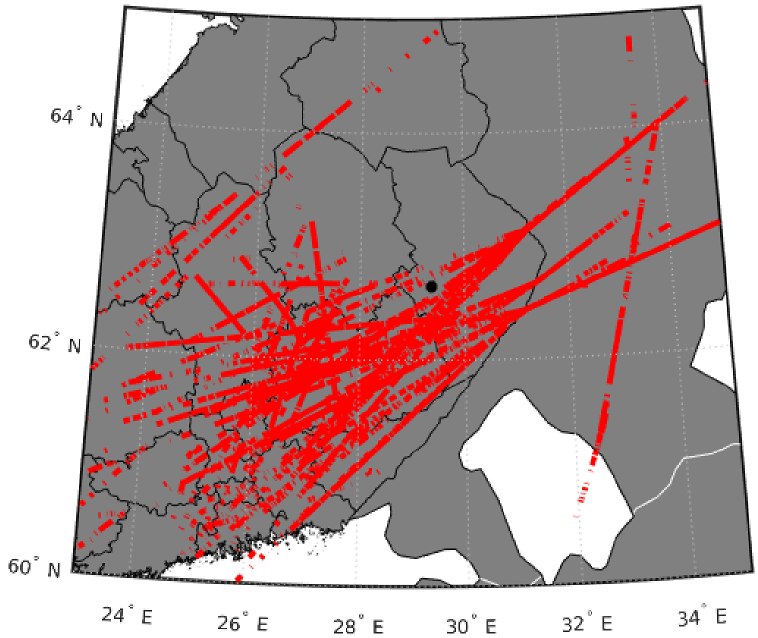

Figure 3: Yagi antenna reception

4.2. Real time observation and tracking of aircraft and high flying ballistic objects

We were able to track a ballistic rocket with our system on 25.4.2018. This was possible with directional yagi antenna from one location. The Moscow TV-transmitter acted as an illuminator of opportunity. TV-transmitters are terrestrial transmitters and to illuminate a target with 100 km height the transmitter has to be distant and powerful.

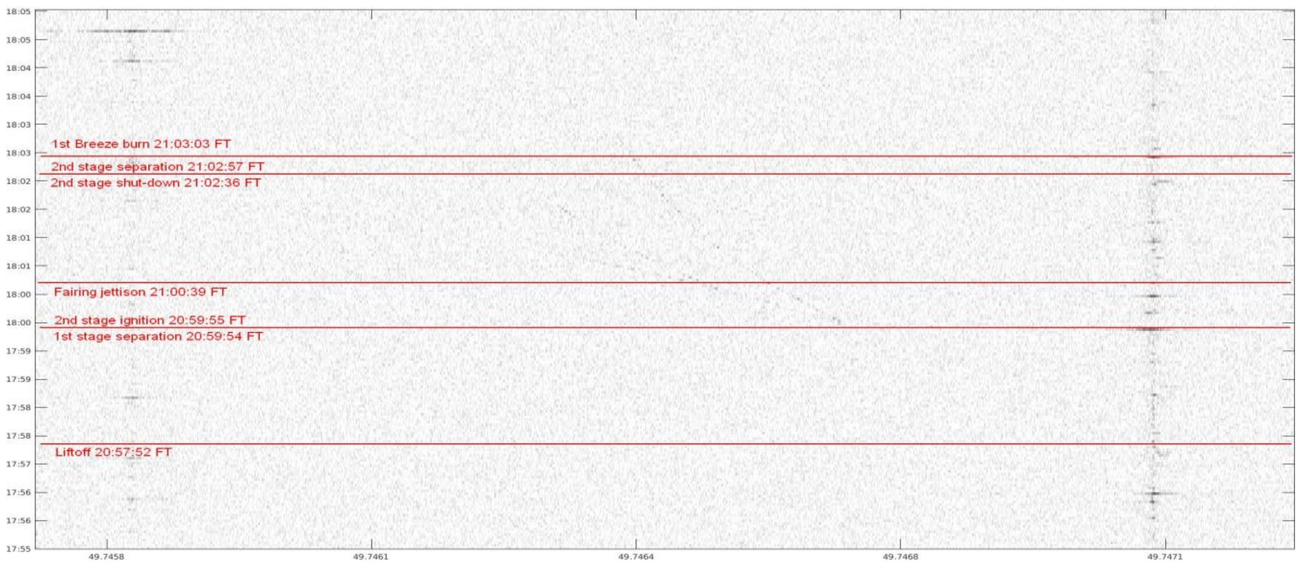

Figure 4: Sentinel 3b

4.3. Producing operative measurement software

Current setup of using remote desktop connection to collect data has been sufficient. The protocol for the data transmission from the receiving nodes to the receiving servers is designed, but is not implemented yet.

4.4. Automatic initialization of the tracks

Initialization in its current state needs directional information from the stations that are connected with a directional yagi antenna. When an aircraft is getting closer to our network from the east and it is not a group of planes, its track can be initialized reliably and robustly. Multiple simultaneous targets still cause the system sometimes to confuse between them.

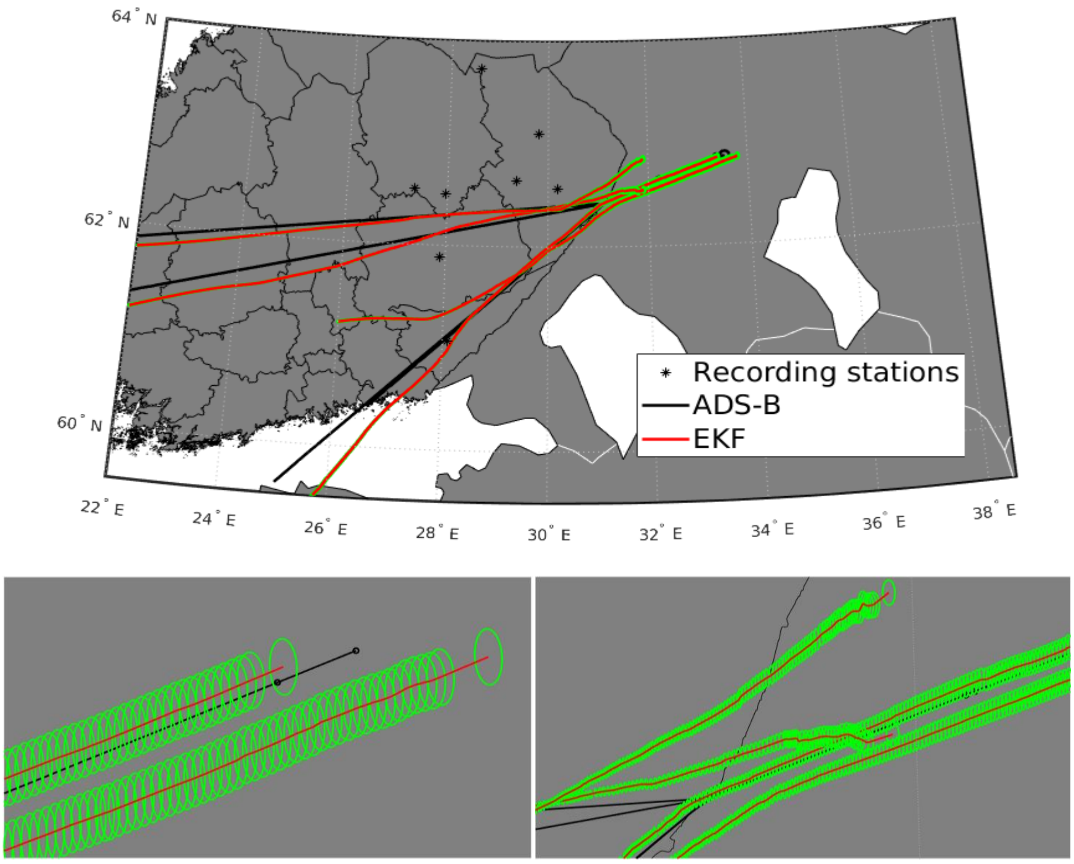

Figure 5: Tracked targets

4.5. Survey on the requirements what would be required to add FM transmitters to the system

To acquire dopplers from FM transmissions coherent reception would be needed. With the current hardware setup coherent receiving is not possible. But it is believed this capability exists in many places so it would be a good target for research collaboration.

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.

The main target of the current year's research was track initialization. A novel method based on look-up tables was developed for that and it appears to perform well with individual targets. In order to give it a wider range still, further investigation with directional antennas that record some phase information were started and were helpful, but the results are not yet conclusive enough for firm statistical assessment.

6. Scientific publishing and other reports produced by the research project

Throughout the years the research group published as journal papers and conference contribution:

[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.

[7] M. Tolonen *et al*., "Resilient Multi-static Forward-scatter Network For Wide Area Air Traffic Monitoring," *2018 19th International Radar Symposium (IRS)*, Bonn, 2018, pp. 1-6.doi:10.23919/IRS.2018.8448070 ISBN-ISSN:2155-5753

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Lappeenrannan Teknillisen Yliopiston Doppler-havaitsemistutkimus on sekä konseptiltaan että toteutustavaltaan muita havaitsemismenetelmiä täydentävä. Jo näillä resursseilla on saatu näytettyä toteen kyky havaita ilahduttavan kaukanakin ilmakehän halki liikkuvia kohteita. Kohteiden tilaestimoinnin menetelmä ei ole ainoa mahdollinen, mutta on valittu, jotta tarkasteltaisiin muitakin seurantamenetelmiä kuin jo hyvin tunnetut. Seurantamenetelmän tuloksia voidaan pitää ”proof-of-concept” -tasona, ja haluttaessa voidaan myöhemmissä tutkimuksissa vertailla eri estimointimenetelmiä.

Esitetyllä Doppler-sirontojen havaitsemismenetelmällä on luonnollisesti samat rajoitukset kuin kaikilla muiden hallinnassa oleviin lähettimiin tukeutuvilla menetelmillä: mitä tapahtuu jos valaisulähetin ei ole käytettävissä. Tutkimuksessa tarkastellut menetelmät ovat joiltakin osin sellaisenaan, joiltakin osin vähän modifioituna sovellettavissa muihinkin lähetelajeihin.

Tutkimus on tuottanut mielenkiintoista tietoa matalien VHF-taajuuksien etenemisestä Suomessa ja lähialueilla ja osoittanut uusia ideointivaihtoehtoja eri turvallisuusviranomaisten tilannekuvan kehitysohjelmille.