Secondary Surveillance Radar (SSR) Flight Inspection - Technology and Practices

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BIOGRAPHY (IES)

Dipl.-Ing. (FH) Maik Ritter studied Computer Science at the University of Applied Sciences in Braunschweig/Wolfenbüttel, Germany and received the Diploma in 2007. Since August 2007, he has been working at the Competence Center Flight Inspection Systems of the Aerodata AG in Braunschweig. His main field of work is the development of firmware and embedded software for flight inspection measurement equipment. Additionally, he integrates the equipment into the AFIS software where further processing, visualization and recording of the raw data is performed.

B.Eng Christopher Dean studied Engineering (Aerospace Avionics) at the Queensland University of Technology and received the Degree in 2008. From 2008 until 2011 he worked as a Systems Engineer at Raytheon Australia on the Defence Air Traffic Control System and then joined AeroPearl in 2011. His main responsibilities are to maintain and manage the Flight Inspection System, ensuring continued compliance with international standards and development of changes and system improvements. In addition, he also performs flight inspection duties and runs other company projects as required.

ABSTRACT

Measurement and analysis of SSR performance has largely been made on the basis of the flight inspection aircraft playing the role of a co-operative, calibrated target, able to generate high quality truth data for accuracy analysis purposes. This is a time consuming process and real time assessment of SSR performance and coverage is often not possible onboard the aircraft itself. Additionally with classic and Mode S RADAR, Multi-Lateration Systems and TCAS adding to the 1030 MHz RF environment, new technology was required to be developed and to be integrated into the flight inspection system for SSR pulse analysis and interference detection.

This paper presents the methods used for such analysis in the past and how they led to the development of new technology able to complete this analysis, airborne and in real time. The hardware/software concept and realization into the airborne system is presented. Also a brief history in development of this system is shown, in order to prove that the integration in a modern and compact flight inspection system is possible.

The effectiveness of the system in the context of SSR flight inspection and additional considerations for the use of monitoring spectrum protection with regards to EU Regulation No 1207/2011 is considered. The EU regulation, effective since the beginning of 2015 requires periodic checks on the 1030 MHz uplink band to prove the intended and specified purpose of a surveillance radar system. As discussed in the flight inspection community, the required checks are not implemented yet, because of the lack of easy to use and cheap solutions, incorporated into a flight inspection system. This paper will show, that solutions already exist and are already in practical use for several years.

Several use-cases are presented, including examples where the capabilities offered by the technology were key to understanding complex interactions in the 1030 MHz RF environment and resolving issues observed in SSR performance. By talking about the 1030 MHz uplink band of an SSR system, the question arises, if also the 1090 MHz downlink needs additional checks for proving that both spectra are safe to use for the surveillance task. It is shown, what has been done in the past to protect the 1090 MHz downlink and how this protection techniques can help in today's flight inspection considerations.

As the mentioned EU regulation has been effective for over 2 years, but widely disregarded in the flight inspection community, it is recommended that awareness of the topic be raised to the flight inspection community and Civil Aviation Authorities.
There is a need for additional, well defined checks during flight inspection of secondary surveillance radar systems and this presentation shows that easy to use and fully integrated technology is already available and that its operational usefulness has been proven.

INTRODUCTION

This paper presents a different approach to SSR inspections and continues with the work previously developed and presented in [1] . The SSR is regarded as an additional facility that will be inspected in flight using dedicated flight inspection equipment and processing. Up until now, only the interrogation side of the radar communication is checked in the FIS. With the introduction of additional hardware, we now have the possibility to monitor and record both interrogation and reply traffic on the 1030 MHz and 1090 MHz spectrums respectively. This new approach allows not only the possibility for in-flight recording of complex interactions in the full SSR spectrum (uplink and downlink), but also opens the door for other uses of the data during the flight inspection for all other navigation aid inspections.

TRANSPONDER PULSE DECODER SYSTEM

A Transponder Pulse Decoder System (TPDS) is an approach to incorporate SSR inspection capability into the FIS. It comprises of SSR receiving hardware with real time processing of the 1030 MHz band and FIS software integration.

TPDB Hardware

In order to process the impulses contained in the 1030 MHz band, a dedicated receiver is required. The Transponder Pulse Decoder Box, depicted in Figure 1 contains a 1030 MHz receiver, DPSK demodulator, real-time impulse and interrogation processor and control and data interfaces to communicate with the flight inspection system.

The internal processing of the TPDB and the integration into the flight inspection software is deeply discussed in [1].

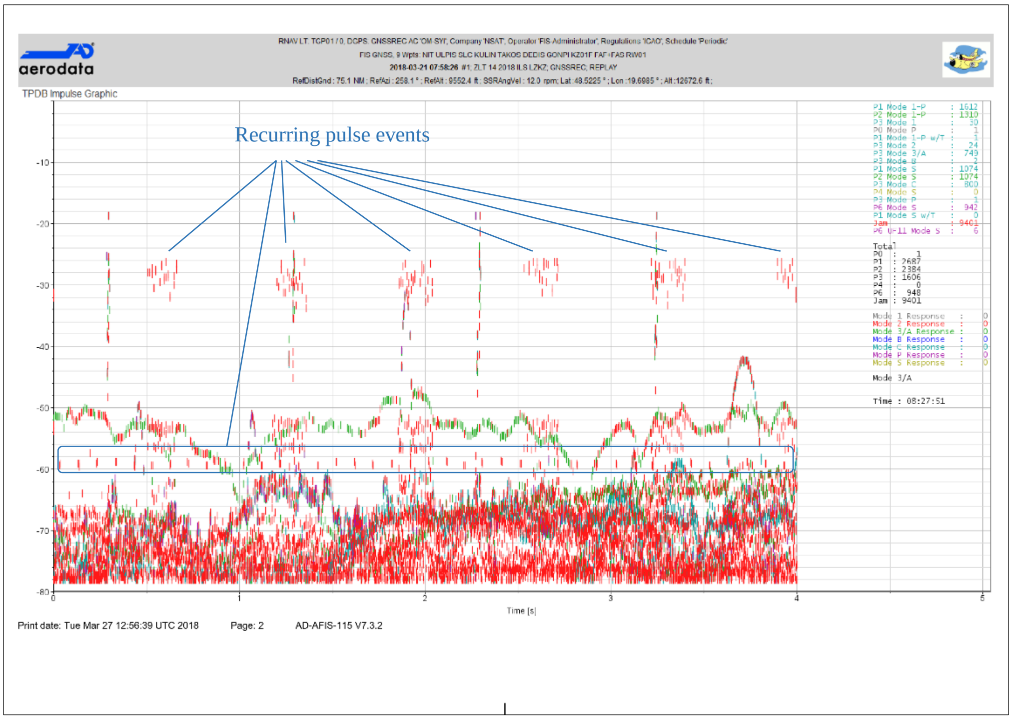
Figure 1: Transponder Pulse Decoder Box (TPDB)

The latest modification of the TPDB hardware included the integration of the 1030 MHz receiver and DPSK demodulator which decreased the size of the system dramatically. Only one device is now needed for the inspection of impulse based SSR interrogations.

SSR Flight Inspection Practices

One of the main purposes of flight inspection is to measure and calibrate the performance of a ground based navigation aid or surveillance system. Ground based navigation systems can normally distinguished by different carrier frequencies on which they operate. The flight inspection receiver is tuned to that carrier frequency and the navigation aid can be measured and calibrated for all the parameters that are required in [2] and [3].

For SSR flight inspection, all ground based interrogators (and even all airborne interrogators) operate on the same frequency of 1030 MHz. In order to inspect a single interrogator, a filtering on the data of the surveillance band has to be implemented. This filtering is also described in [1]. The images Figure 2 to Figure 6 depict the process how the TPDS is able to flight inspect one SSR interrogator on a shared frequency band.



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2018-03-21 07:58:26 #1, ZLT 14 2018 ILS LZKZ; GNSSREC; REPLAY
RefDistGnd : 75.1 NM ; RefAzi : 258.1 ° ; RefAlt : 9552.4 ft; SSRAngVel : 12.0 rpm; Lat :48.5225 ° ; Lon :19.6985 ° ; Alt :12672.6 ft;

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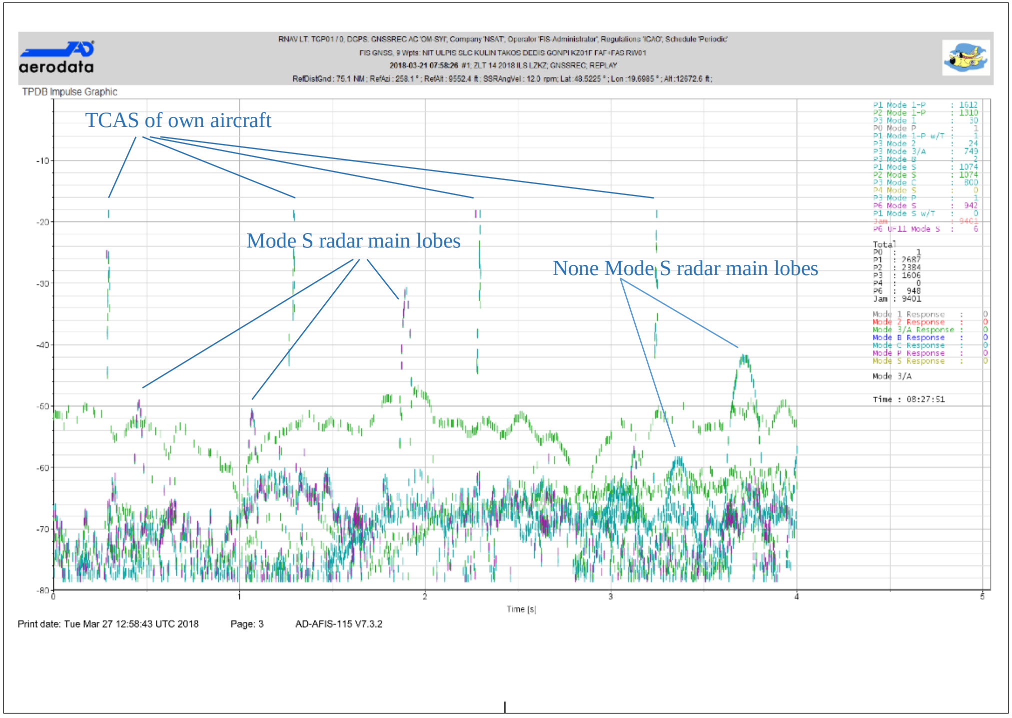
Figure 2: All interrogation impulses for a radar rotation time

Figure 2 is an impulse graphic, which shows all impulses that the TPDB identified during a full radar rotation time. Here, the radar rotation time is 4 seconds. By looking at the legend of the graphic, which also shows the number of all recognized impulse types, the graphic contains around 17000 impulse events. Not all of these impulses are from the SSR interrogator under inspection. In fact, more than 99.9% of the impulses are not of interest for the current inspection.

Due to a filtering based on the interrogator- and station-identifiers in the Mode S protocol, it is possible for the TPDB to mark Mode S P6 impulses as to be received from the interrogator of interest. These interrogation impulses can be made visible by switching off all out-of-interest impulse types from the impulse graphic in the FIS software.



aerodata

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2018-03-21 07:58:26 #1; ZLT 14 2018 ILS LZKZ; GNSSREC; REPLAY
RefDistGnd : 75.1 NM ; RefAzi : 258.1 ° ; RefAlt : 9552.4 ft ; SSRAngVel : 12.0 rpm; Lat :48.5225 ° ; Lon :19.6985 ° ; Alt :12672.6 ft ;

TPDB Impulse Graphic

```
P1 Mode 1-P      : 1612
P2 Mode 1-P      : 1310
P3 Mode 1        :   30
P0 Mode P        :    1
P1 Mode 1-P w/T  :    1
P3 Mode 2        :   24
P3 Mode 3/A      :  749
P3 Mode B        :    2
P1 Mode S        : 1074
P2 Mode S        : 1074
P3 Mode C        :  800
P4 Mode S        :    0
P3 Mode P        :    1
P6 Mode S        :  942
P1 Mode S w/T    :    0
Jam              : 9401
P6 UF11 Mode S   :    6

Total
P0  :    1
P1  : 2687
P2  : 2384
P3  : 1606
P4  :    0
P6  :  948
Jam : 9401

Mode 1 Response   :   0
Mode 2 Response   :   0
Mode 3/A Response :   0
Mode B Response   :   0
Mode C Response   :   0
Mode P Response   :   0
Mode S Response   :   0

Mode 3/A

Time : 08:27:51
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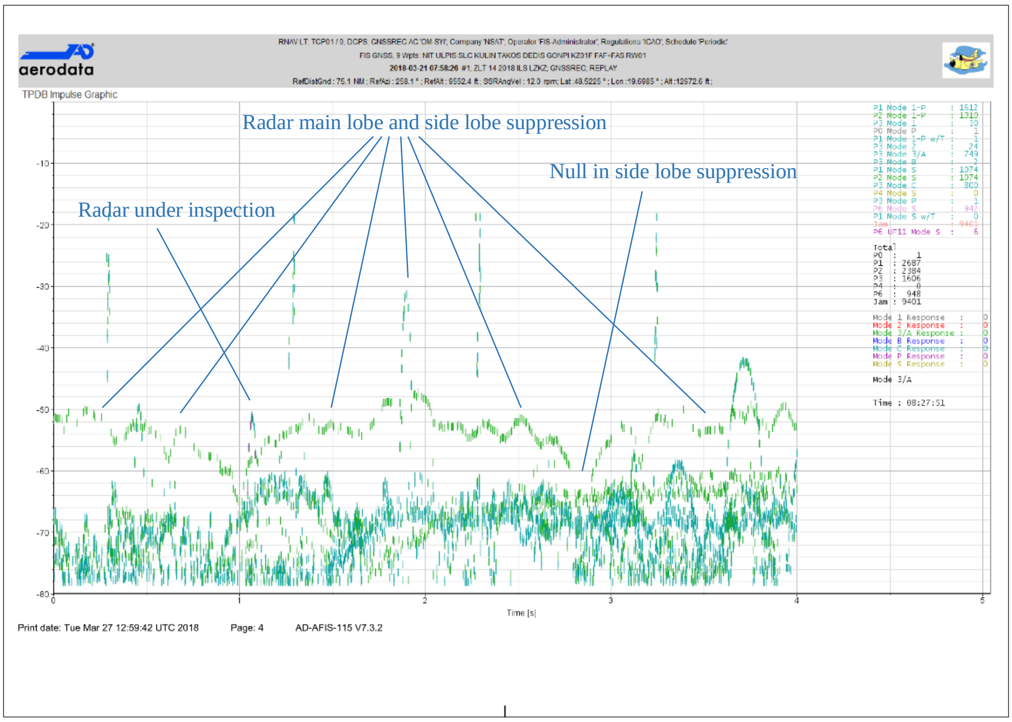
Figure 3: All valid interrogation impulses (JAM excluded)

Figure 3 shows the same impulse graphic with all Jam-impulse events switched off. Jam impulses are events on the 1030 MHz band that have impulse characteristics like an SSR interrogation shows, but these events are not assignable to a valid interrogation. By comparing Figure 2 and Figure 3, some interesting features of the impulse graphic become visible. It is easy to determine recurring events on the impulse graph by just having a quick look at it. In Figure 2, there are regular patterns of Jam-impulses present that contribute to the impulse load on the 1030 MHz band. In Figure 3, where no Jam-impulses are shown, it becomes obvious that these impulse patterns do not contribute to the surveillance task on the 1030 MHz band because there are no valid interrogations present that show the same pattern.

The received interrogations are either an unintended disturbance on the interrogation frequency or interrogations (e.g. for multilateration purposes) that do not obey the specifications regarding impulse-spacing or -width. It has to be mentioned that the TPDB is stricter in recognizing an interrogation as valid as a real transponder would be. This means that it may not be obvious for the operator of the interrogator that the interrogations do not meet the specifications because he might get replies from transponders and therefore assumes the interrogation is within specification and working correctly.

Coming back to the possible observations in Figure 3, a trained operator would immediately spot several radar main lobes, from which, some are Mode S and some are not. Mode S interrogations are immediately recognized by the purple colored P6 impulses. Additionally, the TCAS interrogations of the own aircraft are visible. This view of own TCAS interrogations could be excluded from the raw data out of the TPDB, if the feature of reading the suppression line of the aircraft was enabled. Then, all L-Band transmissions from the flight inspection aircraft would not be recognized by the TPDB.

Still, it is hard to find the main lobe of the radar of interest, since there are at least three Mode S radars visible on the plot. By switching off all non-UF11 filtered Mode S P6 impulses in the graphic, Figure 4 now shows the Mode S radar. It is not the strong radar in the middle of the screen but a much weaker main lobe that is almost not recognizable in Figure 2 with its overwhelming impulse activity information.



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2018-03-21 07:58:26 #1; ZLT 14 2018 ILS LZKZ; GNSSREC; REPLAY
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TPDB Impulse Graphic

```
P1 Mode 1-P        : 1612
P2 Mode 1-P        : 1310
P3 Mode 1          :   30
P0 Mode P          :    1
P1 Mode 1-P w/T    :    1
P3 Mode 2          :   24
P3 Mode 3/A        :  749
P3 Mode B          :    2
P1 Mode S          : 1074
P2 Mode S          : 1074
P3 Mode C          :  800
P4 Mode S          :    0
P3 Mode P          :    1
P6 Mode S          :  942
P1 Mode S w/T      :    0
Jam                : 9401
P6 UF11 Mode S     :    6

Total
P0  :    1
P1  : 2687
P2  : 2384
P3  : 1606
P4  :    0
P6  :  948
Jam : 9401

Mode 1 Response   :   0
Mode 2 Response   :   0
Mode 3/A Response :   0
Mode B Response   :   0
Mode C Response   :   0
Mode P Response   :   0
Mode S Response   :   0

Mode 3/A

Time : 08:27:51
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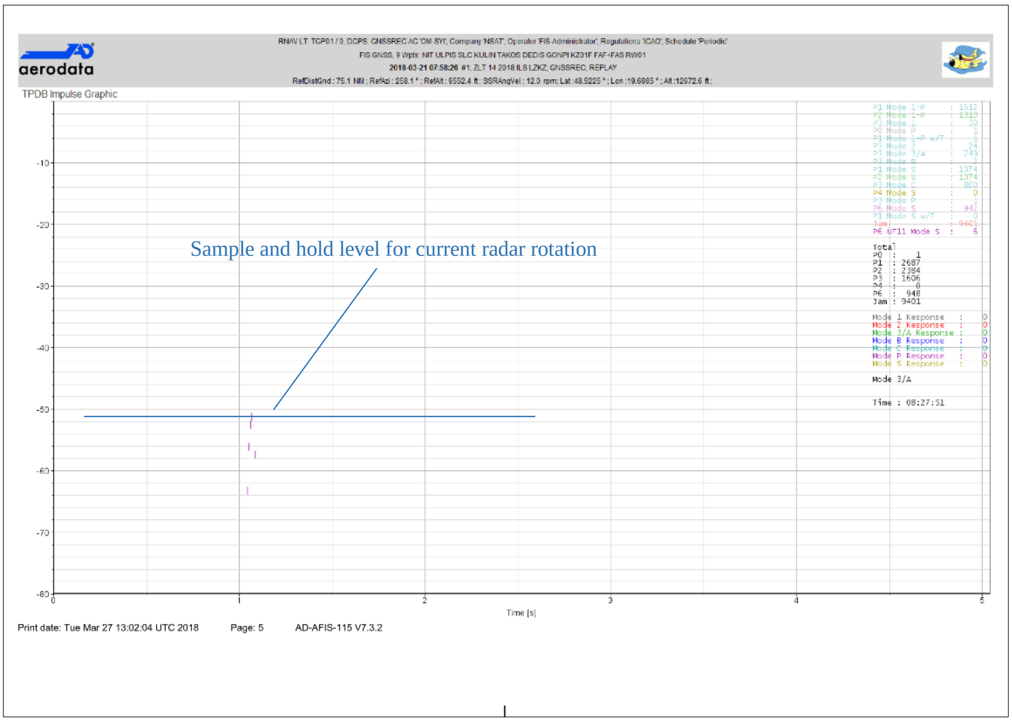
Figure 4: All valid interrogation impulses minus filtered Mode S interrogations

Figure 4 contains many interesting features, one of which is a clearly visible radar with its main lobe in the center of the plot. Additionally, its side lobe suppression “band”, which at one point has nulls which manifests the possibility of false interrogations in that area. However, it is still too much information regarding the focus on the radar under inspection.

Figure 5 finally shows what is interesting for the current inspection. It is the interrogations of that radar that is filtered by its interrogator- and/or surveillance-identifier in the UF11 interrogations. Six interrogations are received from that radar in the current impulse graphic plot.

As it is not very convenient to observe all the impulse graphic plots during an inspection and find the radar interrogations of interest with the above-mentioned procedure, some means of automatic flight inspection features have to be explained.



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RefDistGnd : 75.1 NM ; RefAzi : 258.1 ° ; RefAlt : 9552.4 ft ; SSRAngVel : 12.0 rpm; Lat :48.5225 ° ; Lon :19.6985 ° ; Alt :12672.6 ft ;

TPDB Impulse Graphic

```
P1 Mode 1-P        : 1612
P2 Mode 1-P        : 1310
P3 Mode 1          :   30
P0 Mode P          :    1
P1 Mode 1-P w/T    :    1
P3 Mode 2          :   24
P3 Mode 3/A        :  749
P3 Mode B          :    2
P1 Mode S          : 1074
P2 Mode S          : 1074
P3 Mode C          :  800
P4 Mode S          :    0
P3 Mode P          :    1
P6 Mode S          :  942
P1 Mode S w/T      :    0
Jam                : 9401
P6 UF11 Mode S     :    6

Total
P0  :    1
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P6  :  948
Jam : 9401

Mode 1 Response    :    0
Mode 2 Response    :    0
Mode 3/A Response  :    0
Mode B Response    :    0
Mode C Response    :    0
Mode P Response    :    0
Mode S Response    :    0

Mode 3/A

Time : 08:27:51
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Sample and hold level for current radar rotation

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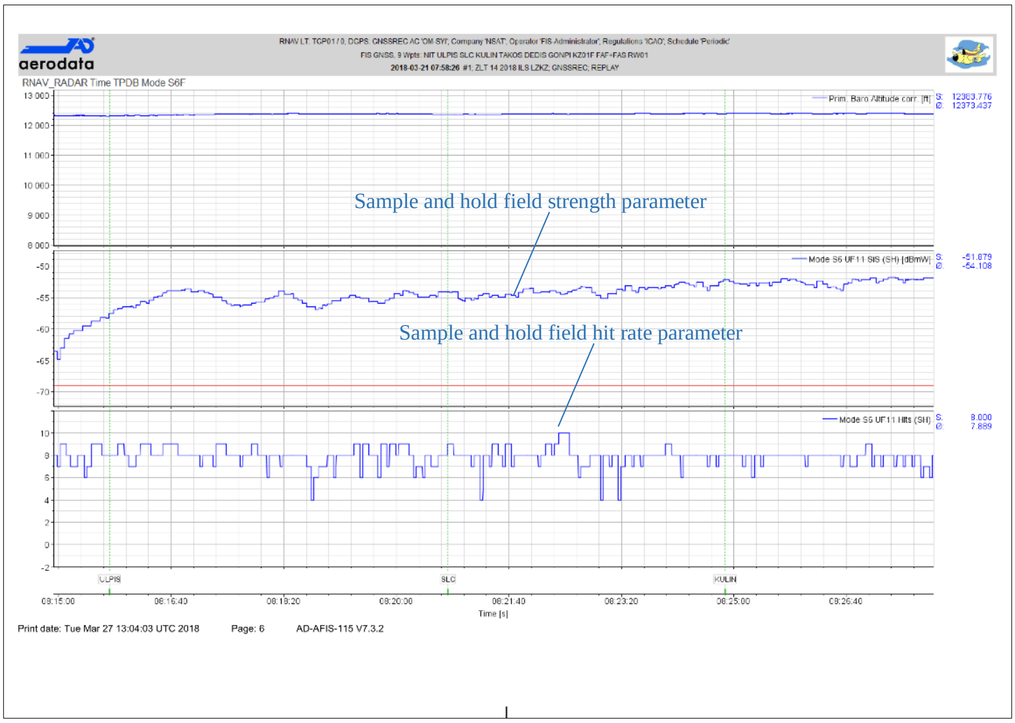
Figure 5: Only filtered Mode S interrogations

In order to automatically measure and judge impulse based signals, it would be useful to find a way to represent the data just like non-impulse based signals as e.g. VOR filed strength. In order to achieve this, Figure 5 shows a so called "sample and hold" level that fixes the maximum signal level of the interrogations from the radar of interest for a defined amount of time. This amount of time is currently defined as one radar rotation + 10%.



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2018-03-21 07:58:26 #1; ZLT 14 2018 ILS LZKZ; GNSSREC; REPLAY

RNAV_RADAR Time TPDB Mode S6F

Sample and hold field strength parameter

Sample and hold field hit rate parameter

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Figure 6: Flight inspection graphic for filtered SSR interrogator

All impulse levels of the UF11 filtered interrogations are stored in a circular buffer, which determines the currently contained maximum level. This maximum level is then put into an additional parameter that is displayed in a standard field strength graph, depicted in Figure 6. The same sample and hold procedure applies for the hit rate parameter of the UF11 filtered radar. The maximum number of valid interrogations, that "hit" the aircraft in a defined period of time (again, one radar rotation time + 10%) is shown in the graphic of Figure 6 as well.

Figure 7, which is a field strength and hit rate plot from the radar that is described above, contains some undesired events that may not have been discovered without the usage of the TPDB. On a descent to final approach, the interrogator field strength of the radar under investigation suddenly drops out for several rotations. Naturally, if there is no interrogator field strength received by the aircraft, there is in fact no interrogation. This also causes a dropout in the hit rate reaching the aircraft. This situation leads to a state where the surveillance of the aircraft is not without interruption. Since the field strength and the hit rate recover after a short period, performance may be considered acceptable. However, to know that there are dropouts in certain spots of the surveillance coverage is most useful information for the future, in case performance continues to degrade and/or other unexpected surveillance problems occur in the area.

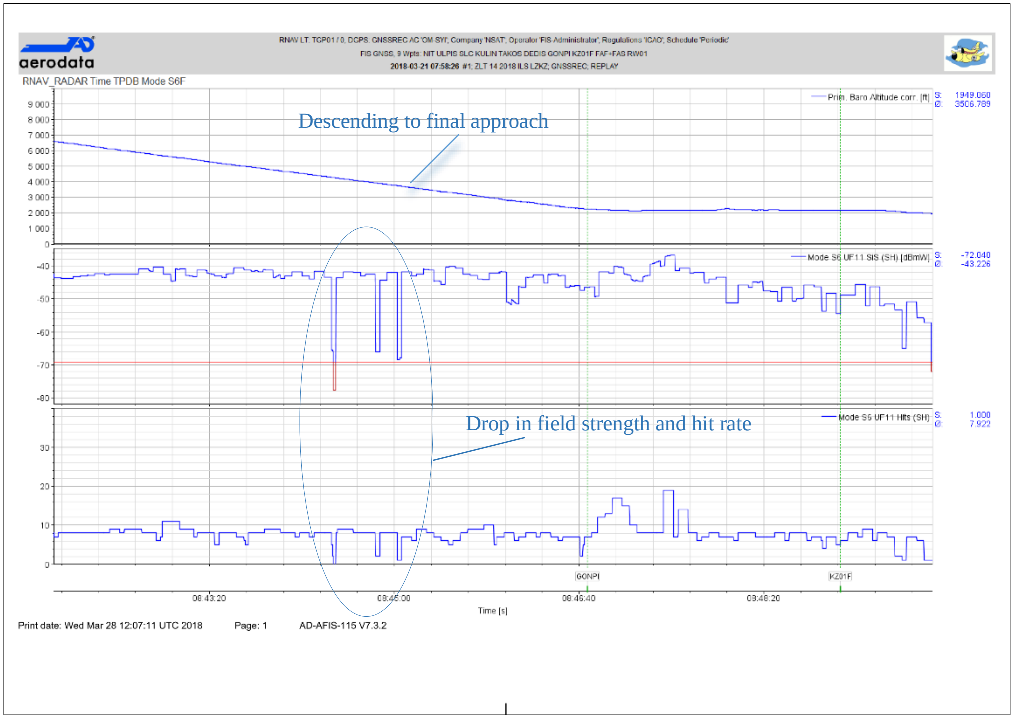

Figure 7: Field strength and hit rate drop

SPECTRUM PROTECTION

Both Annex 10 Volume IV [4] and EU Regulation No 1207/2011 [5] have recommendations and/or requirements on Spectrum Protection. Annex 10 Volume IV paragraph 3.1.2.3.2.4.1 recommends that "*Through investigation and validation, States should ensure that military applications do not unduly affect the existing 1 030/1 090 MHz civil aviation operations environment*", with regard to the military use of the reserved downlink and uplink format codes.

EU Regulation No 1207/2011 [5], Article 6, Spectrum Protection, 1 – 3, states that:
1.*"… a secondary surveillance radar transponder on board any aircraft flying over a Member State is not subject to excessive interrogations that are transmitted by ground-based surveillance interrogators and which either elicit replies or whilst not eliciting a reply are of sufficient power to exceed the minimum threshold level of the receiver of the secondary surveillance radar transponder."*

2. *"… the sum of such interrogations shall not cause the secondary surveillance radar transponder to exceed the rates of reply per second, excluding any squitter transmissions, specified in paragraph 3.1.1.7.9.1 for Mode A/C replies and in paragraph 3.1.2.10.3.7.3 for Mode S replies of Annex 10 to the Chicago Convention, Volume IV, Fourth Edition."*

3. *"…a ground based transmitter (…) does not produce harmful interference on other surveillance systems."*

Annex 10 Volume IV [4], paragraph 3.1.1.7.9.1 states for Mode A/C Replies that "*All transponders shall be capable of continuously generating at least 500 replies per second for a 15-pulse coded reply (…)*". This is the most restrictive requirement for the purposes of Spectrum Protection and EU Regulation No 1207/2011, and hence has been taken as the tolerance.

Annex 10 Volume IV [4], paragraph 3.1.2.10.3.7.3 states for Mode S Replies that *"A transponder capable of transmitting only short Mode S replies shall be able to generate replies at the following rates: 50 Mode S replies in any 1-second interval (…)"*. This again is the most restrictive requirement for the purposes of Spectrum Protection and EU Regulation No 1207/2011, and hence has been taken as the tolerance. At this stage, the type of reply (i.e. short or long) has not been considered, but may be looked at in future work.

1030 MHz Uplink Spectrum Monitoring (TPDS)

To address point 1 and 2 of EU Regulation No 1207/2011 [5], Article 6, the TPDS can be used to sum up all received interrogations with a signal level above the minimum transponder trigger level (-69dBm and -71dBm), separated into Mode A/C interrogations (3/A, C, A/C/S All-Calls) and Mode S interrogations.

For Mode A/C this is a simple exercise of summing the existing 3/A, C and S4 interrogations decoded by the TPDS with a signal level greater than -69dBm and applying a maximum tolerance level of 500 hits per second. Figure 8 provides Mode A/C assessment graphs for a flight check on a standard air route from Sydney to Brisbane.

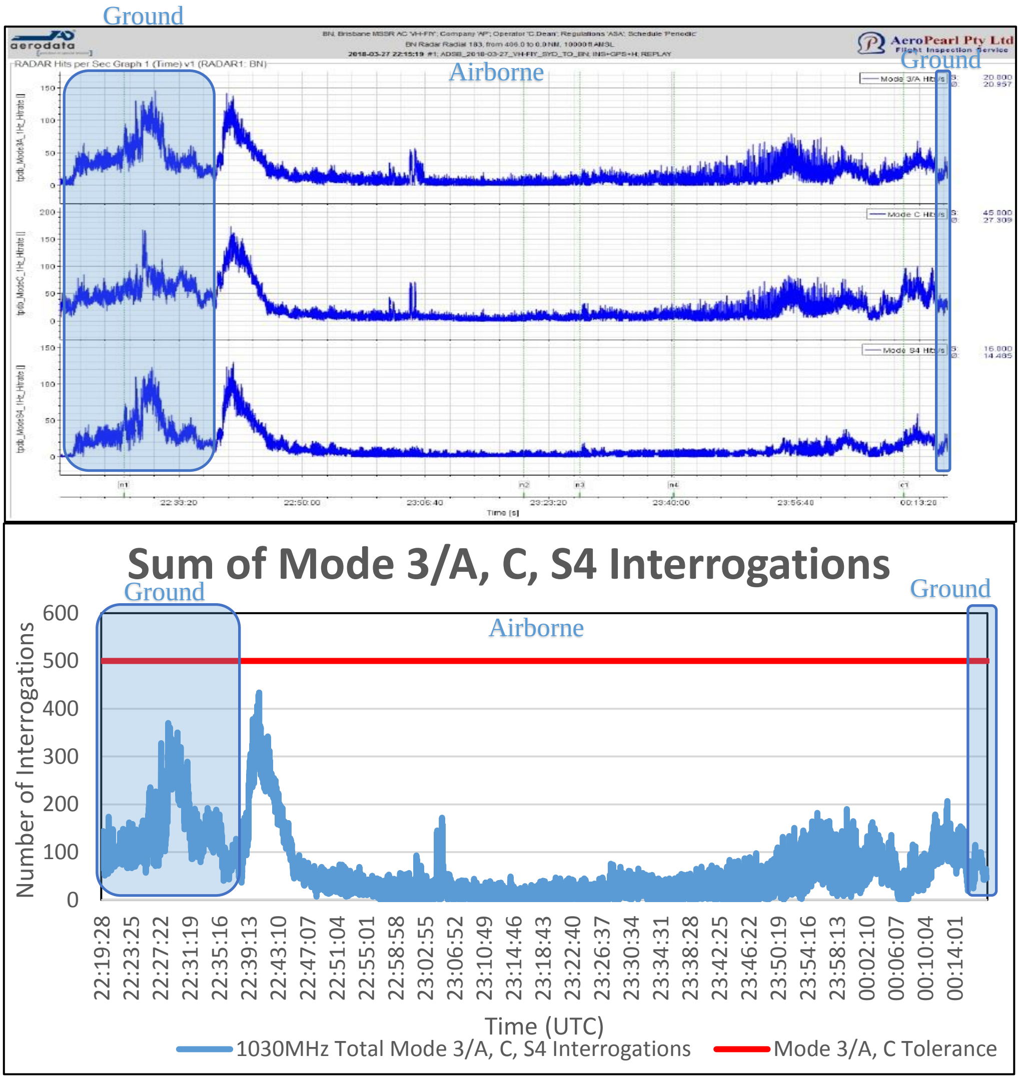

Figure 8 Sum of Mode 3/A, C, S4 Interrogations per Second

For Mode S interrogations, air-to-air interrogations (e.g. TCAS) must also be considered and accounted for. These interrogations ideally would be filtered out based on the UF field (UF0 and UF16 interrogations removed from the hit count). Full implementation of this functionality is a work in progress, but is currently achieved by filtering on a specific ground station using the UF11.

Additionally for Mode S, aircraft addressing must be considered. Hence two parameters are needed, Total Mode S Ground Interrogation Hit Count and Aircraft Filtered Ground Interrogation Hit Count (which includes Mode S All-Calls and only specific aircraft addressed interrogations). The Aircraft Filtered Ground Interrogation Hit Count parameter has not been developed yet. Figure 9 provides an example Mode S assessment.

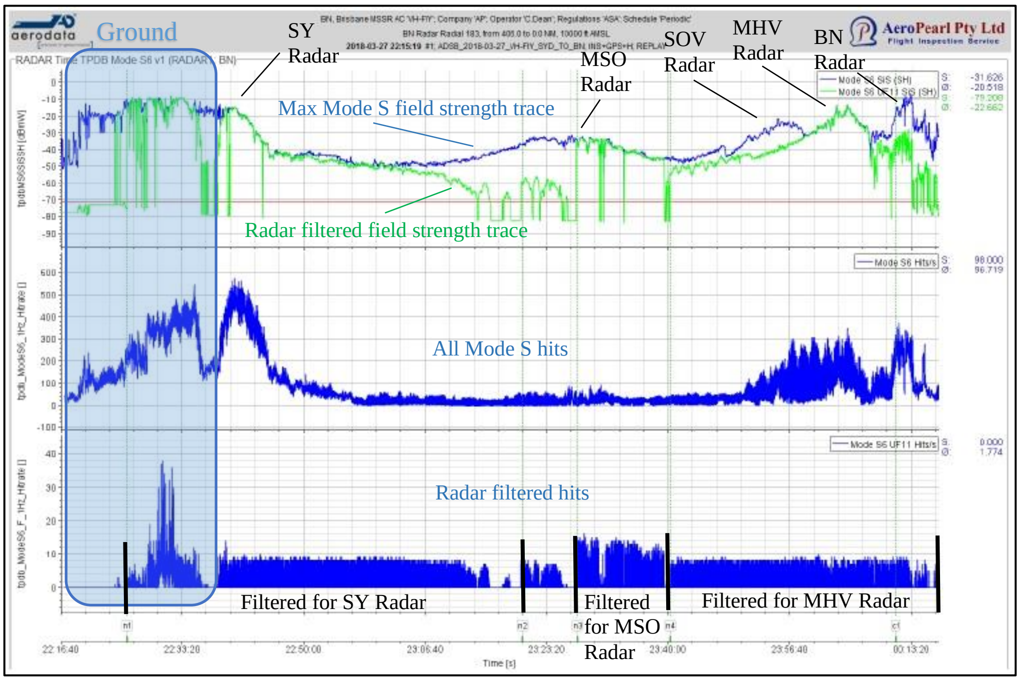

Figure 9 Mode S Ground Station Field Strength and Hit Rate Data

1090 MHz Downlink Spectrum Monitoring (ADSB Monitor)

These measurements provide a way to monitor the 1030MHz Uplink band for ground station interrogations. To complete the full picture and verify that a transponder in the airborne environment is not being required to exceed the rates of reply per second specified above, replies from the aircraft transponder can also be monitored. To test this, an ADSB receiver has initially been used to gather Mode S reply data from the aircraft transponder in real time, though other methods could be employed. The benefit of a dedicated ADSB receiver is that Mode S replies from other aircraft can also be recorded and the data analysed. Due to limitations with the current setup, only Mode S replies have been measured at this stage. Mode 3/A and C replies have not been measured.

The recorded data can be filtered to the specific aircraft transponder using the Mode S address in the reply message, and similarly filtered using the DF field to exclude air-to-air replies. Automatic squitter broadcast should also be accounted for (excluded) in the total reply count. The same tolerances specified above are also applicable. The resulting “Reply Rate per Second” parameter can then be graphed when flying through the area of interest, and overlaid with the 1030 MHz uplink interrogations.

Data has been gathered from the TPDS and ADSB receiver on our flight from Sydney to Brisbane and synchronized for analysis. This data and analysis is presented in the figures and paragraphs below. Figure 10 provides an overlay of the number of Ground Radar filtered interrogations per second measured and the number of replies to ground interrogations per second transmitted by the flight inspection aircraft during this flight.

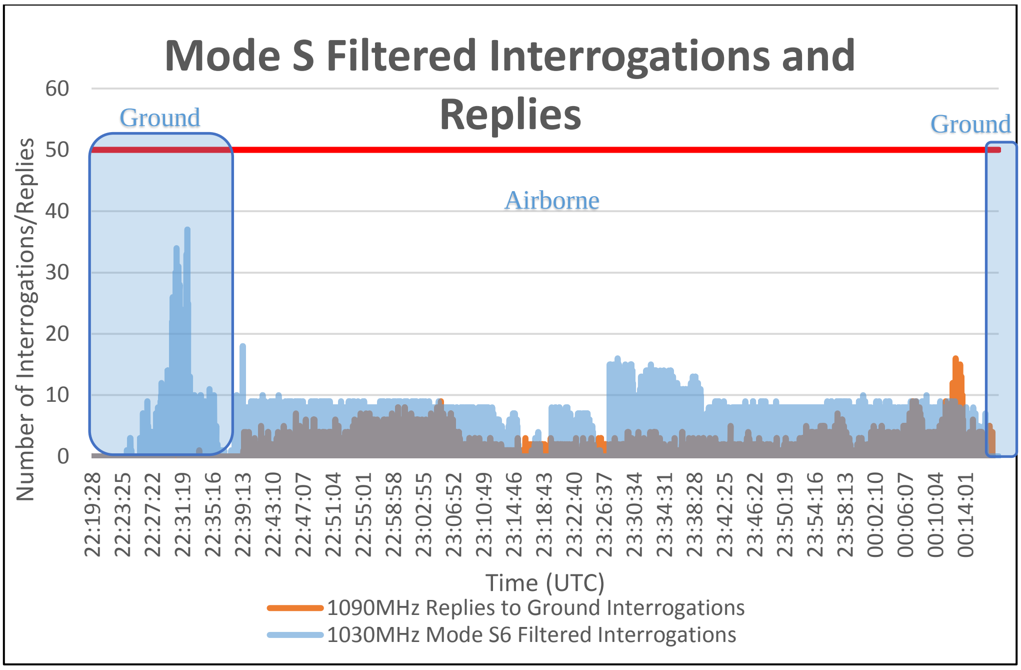

Figure 10 Mode S Filtered Ground Station Interrogations vs Flight Inspection Aircraft Replies

Additionally, total transponder reply rate, including air-to-air replies and squitter, can be observed to judge the full workload of the aircraft transponder. Other information can also be filtered from the ADSB messages by simply decoding the DF and CA portion of the message. An example graph from our flight is show in Figure 11.

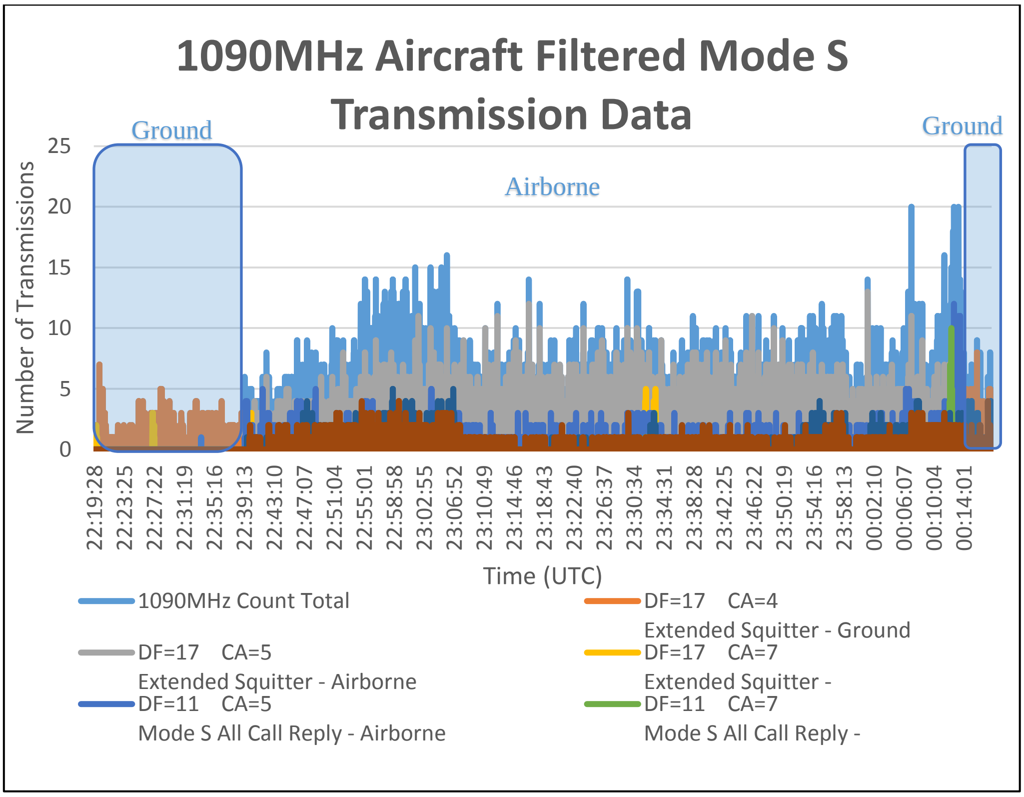

Figure 11 Flight Inspection Aircraft Mode S Various Transmission Data

When both the TPDS measurements and the aircraft transponder reply data can be recorded and synchronized on a single aircraft, deeper analysis covering both the 1030 MHz and 1090 MHz spectrums can be completed simultaneously, and the possibility of a specific airborne transponder reply efficiency parameter is born. This parameter has the potential to be able to provide spectrum efficiency monitoring, showing not just the reply efficiency for one radar but all interrogating sources at once, which could then be used over time to determine when the spectrum is becoming, or has become, overloaded. This may be an area of future development.

Spectrum monitoring can additionally be performed in the 1030 MHz uplink band, utilising the TPDS, by summing the total Mode 3/A, C, S4 and S interrogations, including air-to-air, and by summing all transmissions (replies and squitter) in the 1090 MHz downlink band, utilising the onboard ADSB receiver. This has been performed with data recorded from our flight and graphed in Figure 12.

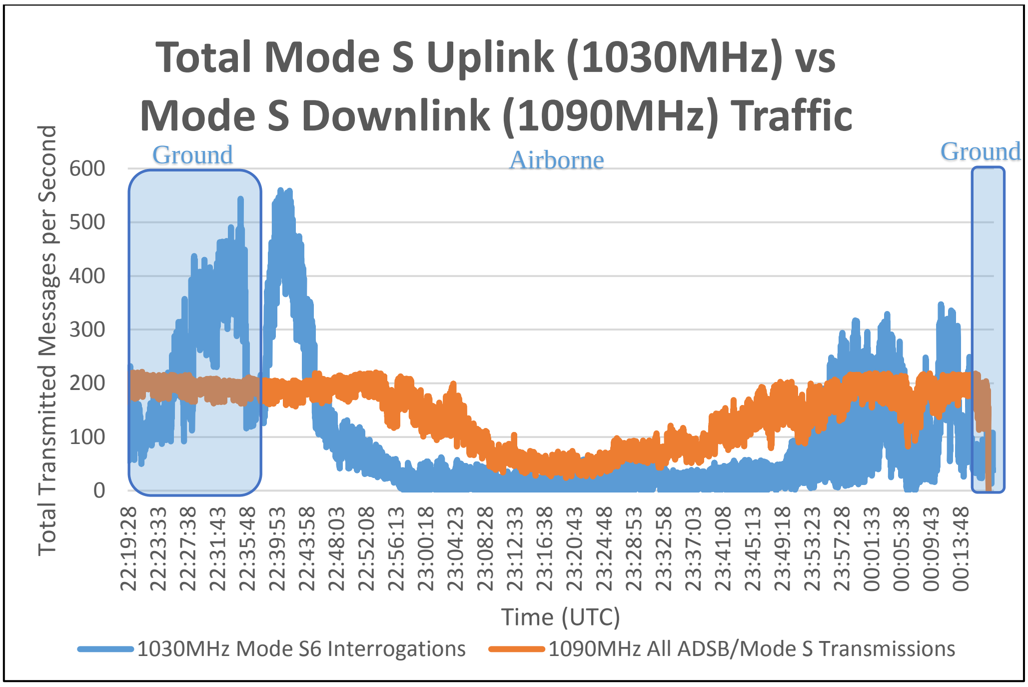

Figure 12 Total Mode S Uplink (1030MHz) vs Mode S Downlink (1090MHz) Downlink Traffic

Looking at this data inversely, by summing the interrogation time of each counted interrogation, we can also identify the total slot time used in each 1 second slot, to gain an understanding and give another perspective on how crowded the spectrum is. The more “slot time” used, the greater the likelihood of an interrogation is going to be overlapped. This was seen in our sample recording where the ADSB receiver recorded a lot of garbled messages in the vicinity of Sydney and Brisbane Airports. Figure 13 provides an example of this from our flight data.

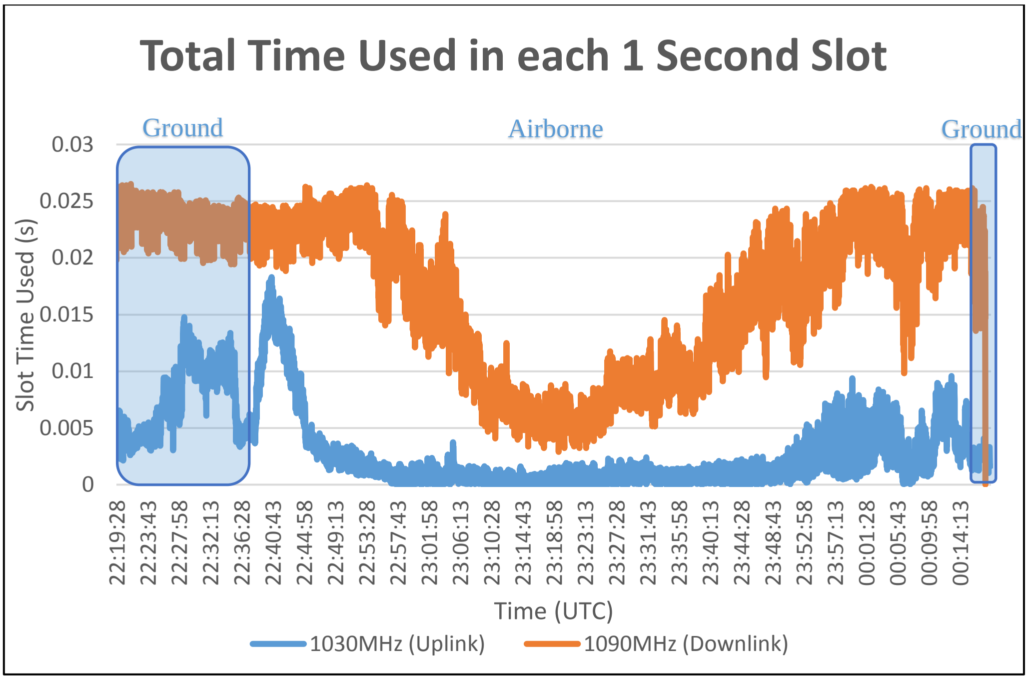

Figure 13 Total Time Used in each 1 Second Slot in the 1030MHz (Uplink) and 1090MHz (Downlink) Band

Although the total number of transmissions in the uplink band when counting all Radar modes and air-to-air interrogations would generally exceed the number of measured replies in the downlink band, the duration of the replies is much longer than the interrogations and therefore consumes more time in each slot, as depicted in above in Figure 13. It is to be noted that Mode 3/A and C replies have not been accounted for in the 1090 MHz downlink band in Figure 13, as they have not been measured. Due to the limitations with the ADSB receiver recording setup, the peak slot usage has also been cutoff at ~25mS. It is expected that in some areas 25mS would be well exceeded.

Profiles for Spectrum Protection Monitoring

From the data measured in flight, it is clear that Spectrum Monitoring is more critical in areas of dense local traffic around airports. This is as expected, but interestingly it is also noted that the Spectrum loading on the ground taxiing around the airport can get close to the levels as seen when airborne in the vicinity of the airport, particularly when taxiing near ground Radars. As such, appropriate monitoring on the ground should be considered in critical areas of the airport. Flight profiles should focus on the approach and departure path, linking procedures (SIDs, STARs) and critical air routes overflying areas covered by multiple Radars. Ideally, measurements would be collected at peak periods to look at maximum load. An orbit around an airport would also give a good idea of loading over a longer period of time.

ADSB FLIGHT INSPECTIONS

While the methods and analysis above have focused on the inspection of ground Radars and the monitoring of the 1030 MHz/1090 MHz spectrums, the addition of an onboard ADSB receiver/monitoring system would enable exact “truth” messages from the flight inspection aircraft to be recorded and compared with receiving ADSB station data. This eliminates the need for data conversion/import tools when comparing data for ADSB inspections, and allows an effective method to measure not only the accuracy of the received data, but also the efficiency of the data link between the aircraft transponder and the ADSB reception station, by tracking and accounting for every transmission.

EFFECTIVE TRACKING OF LOCAL AIRCRAFT

Further exploring the uses of an on-board ADSB receiver/monitoring system, the position of ADSB equipped local aircraft can be tracked. This data can then be used for integration into the flight inspection system for display on the map for situational awareness. Additionally, integration into the flight inspection system would allow for alerts to be generated when another aircraft has entered into specified zones such as ILS protection zones during a flight inspection run, or within a certain radius of the flight inspection aircraft. Influences from other aircraft on measurements could then be specifically attributed to local aircraft, and confidently excluded from being an issue with the ground station or flight inspection aircraft.

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