# Improvement of Weak Signal Detection for ADS-B over Satellite

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***Abstract*—The world's first ADS-B over Satellite (AOS) In-Orbit Demonstrator (IOD) within ESA's PROBA-V mission is operational since May 2013 and has successfully validated the principle of detecting weak Mode S transponder transmissions from a Low Earth Orbit (LEO). A special feature was included in the receiver's firmware that allows to upload new configurations and to activate these by remote access. During mission runtime so far, this has been successfully tested several times. In the meanwhile an improved Mode S correlation mechanism was developed that benefits from the phase coherence of the pulse train from the first Mode S preamble pulse to the fifth format bit. In lab tests it could be shown that the telegram detection rate increased significantly. Moreover, by generating and saving "Low-Confidence Bits" for the 112 Mode S data bits in DF17, there is an additional chance to increase the success rate for error-free demodulation of the telegram in post-processing. The improvement on ADS-B data from space in comparison with the results gained with the non coherent approach will be shown.**

***Index Terms*—Sensor development, ADS-B, Satellite**

## I. INTRODUCTION

In 2013 ESA launched the small satellite PROBA-V [1], carrying among others, the first satellite based Mode S receiver within the frame of the DLR project "ADS-B over Satellite" [2]. Now in space for more then 2.5 years and still operative, this project demonstrated the technical feasibility of a space based ATM (Air Traffic Management) by use of ADS-B signals from Low Earth orbiting satellites.

The detection and demodulation of these Mode S-based ADS-B messages at distances of several hundred kilometers is not comparable to any other ADS-B application on the ground or within airspace. According to the restrictive link budget there is only a small margin for a Mode S correlation and demodulation process to function properly. One must be aware that the hosted payload in LEO is seeking for very weak Mode S signals. These transponder signals were not developed for levels below -90dBm in general, and have very poor correlation properties [3]. Originally, Mode S telegram formats were designed to mitigate some severe SSR problems such as Garbling and FRUIT. A decoding of very weak signals at levels below -90dBm was never intended, and a conventional Mode S preamble correlation of baseband pulses does normally not produce sufficient process gain for a successful detection.

For reasons of available power resources on board the spacecraft, a non-coherent approach was chosen for the correlation process. This process made use of the well known time behaviour of a Mode S signal [4] [5] and thus a successful detection of Mode S formats was based on the correct detection of the four leading pulses of a Mode S preamble.

However, a coherent receiver can provide a better correlation result especially for weak signals with high bit error probability. The new correlation process that is presented in this paper makes use of the phase coherence between single Mode S telegram pulses [6]. In modern airliner transponders, the generated RF pulses origin from a single clock source and the signal is then amplified to achieve the required output level. Typically, the carrier frequency deviation from 1090MHz is less than 100kHz so the received phase is a useful quantity to enhance the correlation process. A special feature is included in the spaceborne receiver that allows to record and downlink the raw 16 bit intermediate frequency (IF) samples at full telegram length for a limited number of Mode S telegrams. This allows improving receivers and correlation algorithms in a lab with the original signal source from space in a box. This innovative technique will be tested and improved during mission runtime since the receiver FPGA configuration and the firmware of its embedded processor can be changed from remote.

## II. IN ORBIT DEMONSTRATION

ADS-B over Satellite on PROBA-V was launched by Europe's newest launcher VEGA [7] on $7^{th}$ of May 2013 at 04:06:31 CEST from the European spaceport Centre Spatial Guyanese (CSG) in French Guyana. The satellite was injected into a polar orbit with the parameters

- Altitude: 820km, SSO
- LTDN: 10h30
- Inclination: 98.8°
- Orbital period: 102 minutes

The ADS-B receiver on board the space craft is non stop operational. Its receiving antennas are coupled with a power divider, resulting in a single beam with a half power beam width of around 73° on the elevation and 33° on the azimuth

TABLE I
ANTENNA PARAMETERS

| Description | Value |
|---|---|
| Type | Planar |
| Frequency | 1090MHz |
| Gain | 10dBi |
| $\text{HPBW}_{AZ}$ | 33° |
| $\text{HPBW}_{EL}$ | 73° |
| Polarization | right hand |

Fig. 1. Satellite Footprint on Earth, Earth Graphics ©NASA

axis. In theory the -3dB footprint on ground is about 750 by 1500 kilometers, the effective maximum detection range is about 900 by 2000 kilometers with a gain of about 10dBi.

In Figure 1 the resulting ground track is shown, indicating an incomplete coverage of the earth in 24 hours due to the narrow field of view.

PROBA-V and its technology demonstrators, including ADS-B over Satellite, are still operational, providing scientific data to the user community of vegetation data.

## III. RECEIVER TECHNOLOGY

Originally, the Mode S format which provides the DF17 extended squitter was not defined to provide good correlation results at poor signal-to-noise ratios. It was introduced in the 1980s as a replacement for the old ATCRBS (Mode A/C) Secondary Surveillance Radar. In case of a rotating radars having antenna gains of ≈30dBi, the receiver level of detected aircraft within its service volume should be -90dB or more as it was already with Mode A/C. Mode S telegrams shall be identified and clearly separated from Mode A/C frames at reasonable effort using signal processing available decades ago [3].

As the receiver directly samples the band pass signal at an intermediate frequency (IF), all further correlation processing and demodulation work is done within a FPGA. In contrast to the standard correlation scheme where the first step is usually to form a baseband signal (pulse video) out of a quadrature demodulator, here the correlation directly uses the raw IF samples. Using 70MHz IF and 105MHz sampling rate, the signal falls into the second *Nyquist zone* and results in an effective undersampled IF of 35MHz. Hence, this IF is threefold oversampled which provides a constant 120° phase shift of consecutive samples.

### A. Current Mode S detection: Single pulse ACF

The FPGA configuration which is currently in use has a correlator that identifies single Mode S pulses and detects a proper arrangement of their occurrences in time. A single pulse width of 0.5$\mu s$ provides 52 Samples to feed a phase and amplitude based autocorrelation function (ACF). An ACF with this model sequence is steadily applied to all incoming IF samples. In information theory, this is also referred to as a *matched filter* [8]. So both amplitude and phase information is used which provides a higher process gain compared to conventional methods which mostly process the video signal only.

If the four preamble pulses and five Mode S format pulses are found at their nominal positions within an allowed uncertainty in time, then a DF17 is detected and further bit demodulation starts. This method is successfully operational since May 2013 and gives sufficient decoding results.

### B. Fully coherent correlation

Most of modern airline transponders have base temperature-controlled crystal oscillators (TCXO) from which the phase of all transmitted pulses are derived. So the pulse train of a Mode S telegram is fully phase-coherent which is a prerequisite to increase the ACF length significantly. Inherently, the process gain increases and the result of the ACF should give a much steeper main maximum and therefore a point in time that is more precise to start the demodulation bit clock. A generic method that detects the phase coherence and benefits from the precise time stamp for both Mode S uplink and downlink formats is given by [6]

Now a model sequence which has predefined phase and amplitude values over a period of 13$\mu s$ fully comprises the Mode S preamble and the first five format bits. This sequence is the constant prefix for all DF17 extended squitter telegrams. Instead of only 52 values, the effective ACF length is now

$$9 \cdot 0.5\mu s \cdot 105 \text{ Samples}/\mu s = 473 \text{ Samples} ,$$

omitting the noise in the pulse gaps.

In Figure 2 the correlation of a high-level Mode S telegram is shown. From the LEO point of view, even this level -95dBm is quite strong since most signals from earth surface or airspace are much weaker and close to channel noise. The IF sample curve in this diagram gives an idea of a Mode S telegram and its single pulses, whereas the ACF clearly points out an absolute maximum at the end oft the fifth format pulse. However, there are numerous side lobes showing different magnitudes to be separated from the main lobe. Some more criteria must be introduced to obtain the main maximum that defines the best starting point in time to demodulate the remaining 112 (or 56 if short DF) pulse-positioned data bits. Among others, these criteria are:

- threshold ratio of main and side lobes
- number of maxima above a minimum trigger level preceding and succeeding a main lobe

If the ACF is applied to significantly weaker signals, its curve still shows the same characteristic as given in Figure 3 for a DF17 telegram at -106dBm. From the IF samples alone the occurrence of a Mode S starting sequence is hardly discernible, whereas the ACF used with the named criteria still shows good results which allows to start the demodulation bit clock correctly.

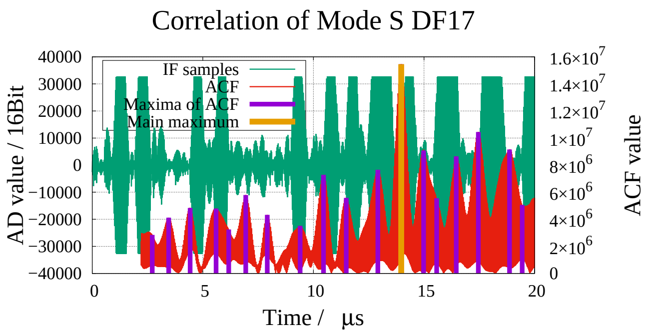


Fig. 2. Fully coherent ACF curve at level -95dBm

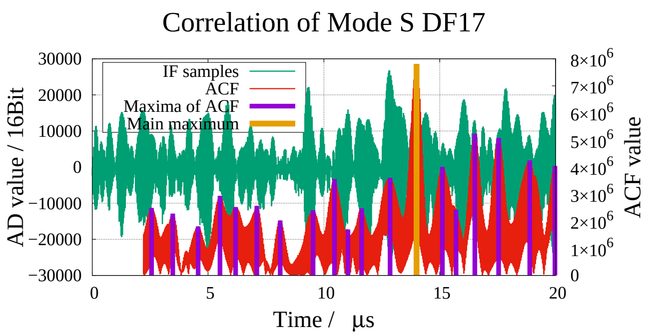


Fig. 3. Fully coherent ACF curve at level -106dBm

### C. Comparison of efficiency

Now the efficiency of the old the single-pulse correlation and the fully coherent method will be compared. The correlator's probability of detection (PoD) Mode S telegrams across a range of signal levels from a large number of telegrams is an appropriate performance test.

In Figures 4 and 5 the DF17 telegram detection only and a subsequent error-free bit demodulation success is given with two curves each for both methods. Focussing on the 50% point of the PoD, there is a difference in process gain of roughly 7.5dB between the two techniques. The success of error-free demodulation is nearly identical for the single-pulse correlator, in contrast to a gap of 4dB for the fully coherent method. A 3dB process gain for error-free detection of this method can be derived from these curves.

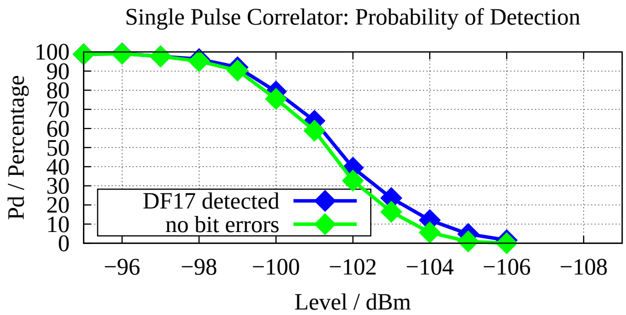


Fig. 4. Single Pulse Correlator, PoD

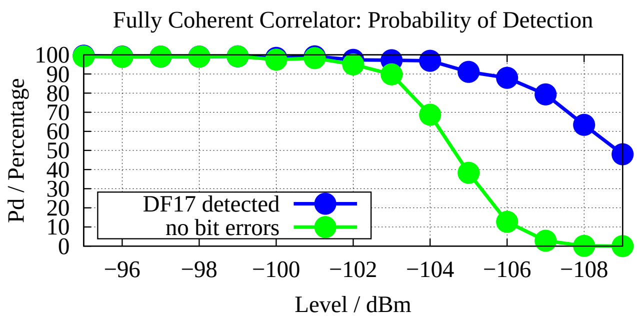


Fig. 5. Fully Coherent Correlator, PoD

### D. Bit demodulation

The Mode S downlink format has a Pulse Position Modulation scheme. A single bit's value is determined from a $0.5\mu$s pulse located in either the left ("1") or right ("0") half of a $1\mu$s chip. Starting at $8\mu s$ from the rise of the first preamble pulse, 112 pulse positions have to be successfully identified for the whole DF17 telegram to become valid. The last part of the telegram contains 24 parity check bits generated from the preceding part of the transmission, using a cyclic polynominal code.

In the present correlator, the demodulation is built on the single-pulse correlation already introduced in section III-A. The continuous correlation function therefore provides the distribution of pulse energy in the specific bit cells. In Figure 6 this ACF is shown for the first 12 data bits of a weak DF17 at the level -106dBm. The lower sequence of ones and zeros denotes the found bit values based on the detected energy maximum in the two half chips. If very little difference in energy between the half chips is found, the bit result is likely to be wrong. In the diagram the red character 'L' denotes the low confidence of specific bits.

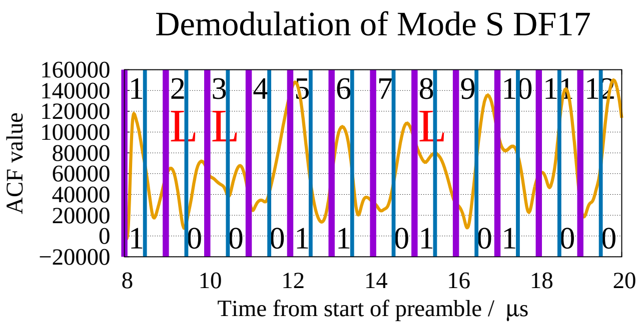


Fig. 6. Correlation of demodulated bits with low-confidence indication

It is another improvement of the new correlator to the derive and save these so-called Mode S *low-confidence bits* [9] for all demodulated data bits. These were originally used to perform a real-time error correction in a radar: whenever a decoded reply contains errors, error correction is attempted if the total number of low-confidence bits in the reply does not exceed a preset threshold. The use of this threshold minimizes the possibility of erroneously "correcting" a reply that contains a very large number of errors.

In a radar, a real-time error correction will be successful only if:

1) all errors are confined within a span of 24 contiguous bits
2) all errors occur in bits flagged as low confidence

In the IOD, there is no need for a real-time correction of erroneous telegrams. All error correction can be done in post-processing with downlink data available. Up to now, there were no attempts made to process these low-confidence bits, since the upload process to PROBA-V still needs to be carried out. By applying the error correction it is expected that the green curve of successful demodulation in Figure 5 moves some decibels to the right.

In general, both the preamble detection and the demodulation process can be fully parametrized. There is some experimental work to be done on the gained data to find out the best parameters to obtain more error-free DF17 and hence, more valid ADS-B positions.

## IV. In Orbit Results

### A. The Performance Indicators

The performance indicators for space based ADS-B surveillance described in this document have been selected in order to be as close as possible to existing ADS-B standards from which we also derived the requirements. This will allow for a direct comparison of space based and ground based ADS-B surveillance in the future and therefore for the assessment and proof, that space based ADS-B surveillance is not only technically feasible but also operationally applicable. The performance indicators selected are:

- Received Signal Power
- Probability of Target Acquisition
  The probability of target acquisition (PTA) is defined as the percentage ratio between the actual number of targets detected and the expected number of targets to be detected within a certain area or time of observation. *Detection* means the provision of positional data, i.e. the reception of at least one ADS-B position message.
- Probability of Detection
  The probability of detection (POD) is defined as the percentage ratio between the actual number of position messages received and the expected number of position messages for a target.
- Probability of Identification
  The probability of identification (POI) is the percentage ratio between the actual number of identification messages received and the expected number of identification messages for a target.
- Preamble Detection Rate
  The preamble detection rate indicates the overall number of detected Mode S preambles and the ratio of correctly received short and long squitters (Type of Downlink Format 11 and 17)

A Mode S transponder transmits the position information and identification by different ADS-B messages and with different transmission rates. For airborne position messages the transmission rate is 2Hz and for identification and category messages when airborne the transmission rate is 0.2Hz, alternately between the top and bottom mounted antenna[10]. For space based performance parameters, only the top antenna is taken into consideration.

### B. Non Coherent Preamble Detection

As described in section IV the key factor for the successful detection and demodulation of an ADS-B message is the detection of the four preamble pulses and five Mode S format pulses. The ADS-B receiver on PROBA-V is capable to detect any Mode S format on 1090MHz and to decode any bit error free DF11 or DF17. In table II and III a summary of detected message types per month is given, including the ratio of correctly and incorrectly received message types. These are:

- DF00: Short air-air surveillance (ACAS)
- DF04: Surveillance, altitude reply
- DF05: Surveillance, identify reply
- DF11: Mode S, Short Squitter, All-call reply
- DF16: Long air-air surveillance (ACAS)
- DF17: Mode S, Extended Squitter (carrying ADS-B)
- DF18: Mode S, Extended Squitter (non-transponder, ground)
- DF19: Mode S, Extended Squitter (Military)
- rDF11: Ratio of correctly received short squitter
- rDF17: Ratio of correctly received long squitter (carrying ADS-B)

The result for the non coherent receiver shows an error free demodulation of about 52% in average for an Extended Squitter with 112 bit message length, while the ratio for the short squitter (56bit) is above 56% in average. It has to be investigated on the IOD weather the improved correlator will not only yield a higher absolute number of detected Mode S

TABLE II
NUMBER OF DETECTED MESSAGE TYPES I

| Mon | DF00 | DF04 | DF05 | DF11 | rDF11 |
|---|---|---|---|---|---|
| Feb | 3.015.498 | 1.212.367 | 851.724 | 3.073.044 | 58.31 |
| Mar | 4.151.454 | 1.708.267 | 1.217.549 | 4.277.600 | 57.77 |
| Apr | 4.341.180 | 1.850.224 | 1.335.557 | 4.510.807 | 55.53 |
| May | 4.390.242 | 1.808.053 | 1.316.937 | 4.560.862 | 57.12 |
| Jun | 4.489.120 | 1.897.918 | 1.374.622 | 4.737.297 | 56.40 |
| Jul | 3.788.887 | 1.540.754 | 1.114.601 | 3.832.409 | 56.30 |
| Aug | 4.569.944 | 1.860.238 | 1.350.113 | 4.707.369 | 56.49 |
| Sep | 3.988.076 | 1.718.612 | 1.264.088 | 4.240.933 | 56.83 |

TABLE III
NUMBER OF DETECTED MESSAGE TYPES II

| Mon | DF16 | DF17 | rDF17 | DF18 | DF19 |
|---|---|---|---|---|---|
| Feb | 695.085 | 3.915.854 | 53.31 | 983.645 | 594.794 |
| Mar | 1.001.749 | 5.656.390 | 53.34 | 859.490 | 1.317.027 |
| Apr | 1.108.799 | 6.036.705 | 51.50 | 1.017.196 | 946.022 |
| Mai | 1.105.280 | 6.121.437 | 52.68 | 987.774 | 939.118 |
| Jun | 1.176.832 | 6.133.437 | 53.20 | 1.050.296 | 994.024 |
| Jul | 963.383 | 5.141.533 | 51.99 | 849.320 | 806.325 |
| Aug | 1.204.221 | 6.489.297 | 52.19 | 1.030.257 | 998.509 |
| Sep | 1.076.588 | 5.835.325 | 52.57 | 957.814 | 889.964 |

messages but also a higher ratio of error free vs. erroneous messages.

### *C. Received Signal Power*

Once a Mode S message has been correctly received by the spacecraft, a success factor is calculated which is called correlation gain or correlation success. With this parameter a conclusion can be drawn that results in the overall received signal power. In Figure 7 the sensitivity of the receiver is shown while Figure 8 shows the detected messages over correlation gain for a dedicated satellite pass. It can be seen that the majority of received Mode S short and long squitters have a signal power between -97 and -101dBm. According to Figure 5 we expect that the curve's peak shifts some decibel towards lower levels. As can be seen in Figure 9 the critical grazing angle of the IOD is about 55° with the majority of received Mode S squitters between 15° and 40°. The decrease towards the nadir direction can be explained with the cone of silence [10] and is caused by the radiation characteristic of the aircraft ATC antenna.

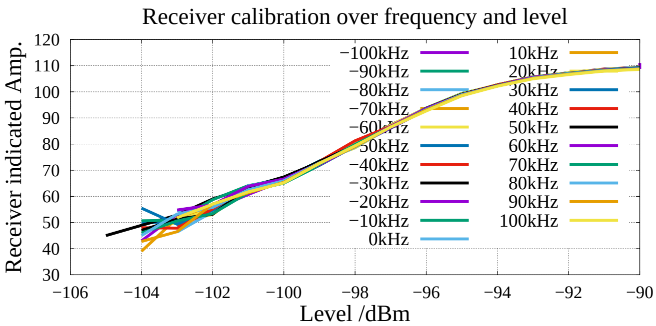


Fig. 7. Receiver Calibration Curve

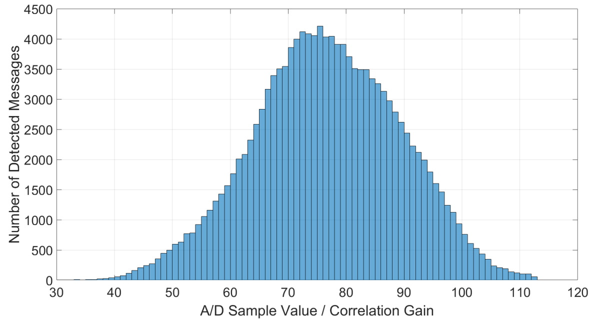


Fig. 8. Correlation Gain

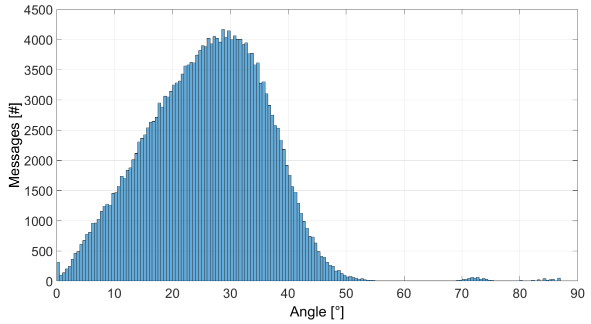


Fig. 9. Critical Grazing Angle

### *D. Performance Results*

With the described performance parameters it is possible to estimate the potential of space based ADS-B region by region on the one hand, and the total loss of information e.g. due to garbling on the other. In table IV the different performance parameters are described for each region in July 2015, where any region is a sector of 30 by 30°, thus covering the whole globe. Additionally to the 18 regions an average for ground based ADS-B messages is presented in the table. The Probability of Target Acquisition shows in general very high percentage in all regions with a significant decrease when an aircraft is on the ground. This is consistent with the significant decrease of the Probability of Detection if an aircraft is on the ground while the Probability of Identification on Ground is much higher compared to an aircraft that is airborne. Obviously the transmission rate for the aircraft identification on ground increases while the transmission rate for the position decreases. A PTA value lower than 100% means that the spacecraft received either a short Mode S Squitter carrying the aircraft's 24 bit transponder address or a long Mode S Squitter with the identification, velocity or status message but without any or with only incomplete position information.

## V. SUMMARY

It has been shown by measurements in a lab environment that a coherent demodulation approach significantly increases the telegram detection rate. It can be expected that the absolute overall number of detected Mode S messages on the satellite

TABLE IV
PERFORMANCE INDICATORS

| Region [#] | Region | POD[%] | POI[%] | PTA[%] |
|---|---|---|---|---|
| 1 | Alaska | 13,49 | 11,17 | 93,50 |
| 2 | North America | 13,68 | 14,38 | 92,39 |
| 3 | NATS | 14,36 | 15,18 | 91,95 |
| 4 | Europe/Russia | 17,86 | 16,65 | 91,82 |
| 5 | Russia | 15,32 | 17,91 | 92,68 |
| 6 | Eastern Russia | 13,83 | 15,39 | 93,51 |
| 7 | Pacific | 14,77 | 13,33 | 95,10 |
| 8 | Central America | 18,55 | 19,80 | 93,54 |
| 9 | Atlantic | 17,06 | 19,88 | 93,39 |
| 10 | Africa | 15,84 | 17,03 | 92,16 |
| 11 | Indian Ocean | 15,09 | 17,32 | 92,54 |
| 12 | Australia | 14,62 | 17,30 | 91,37 |
| 13 | S.Pacific Ocean | 32,17 | 20,51 | 100 |
| 14 | South America | 21,01 | 22,47 | 89,02 |
| 15 | South Atlantic | 14,68 | 20,88 | 96,77 |
| 16 | Southern Ocean | 12,16 | 16,64 | 96,86 |
| 17 | S.Indian Ocean | 19,83 | 14,14 | 81,82 |
| 18 | Australia 2 | 19,15 | 19,10 | 97,20 |
|  | Ground | 8,14 | 26,97 | 65,11 |

will increase accordingly with a noticeable more telegrams at signal levels lower than -100dBm. However, at time of finalization of this paper the uplink of the new correlation mechanism to the space borne receiver could not yet been done. Instead, this paper presented the performance parameters of the non-coherent receiver on PROBA-V. Once the upload of the new firmware has taken place a comparison between performance parameters with coherent and non-coherent detection has to be done.

## ACKNOWLEDGEMENT

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