estec

European Space Research
and Technology Centre
Keplerlaan 1
2201 AZ Noordwijk
The Netherlands
T +31 (0)71 565 6565
F +31 (0)71 565 6040
www.esa.int

DOCUMENT

Determination of levels of saturation from in-orbit CryoSat-2 SIRAL-2 data and other observations

Prepared by	**Robert Cullen**
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1 INTRODUCTION

This draft note provides an analysis as to whether or not the SIRAL-2 receiver is saturated during science data acquisition in SAR modes for four cases including two (cases A and B) presented during the EUMETSAT SAR meeting (26th June 2013).

- Case A: An acquisition over ocean displaying a response that has been historically termed Flat Sea Effect (FSE) but also referred to as σ^0 bloom. Here we refer to FSE, though this may also not be the best term.
- Case B: A pass over Volga river delta (inland water/land) onto the Caspian sea.
- Case C: 1 month (June 2013) of global SAR Level 0.
- Case D: SAR Tracking echoes (not provided in this draft).

Cases A and B concern results presented at NOC in June 2013.
In addition, some other observations are made regarding SIRAL data.

1.1 Summary

Of the three SAR data cases analysed in this draft we find in Case B that 1 burst out of 4000 to be clearly saturated and conclude the instrument is operating nominally in terms of gain control. The reason being the instrument functioning at its natural timing cycle cannot cope with a rapid land to calm water backscatter transition if the backscatter change is outside of specification. A few other bursts are close to saturation.
In terms of Case A, the gain control is acting nominally keeping the power level into the digital processing unit very stable, though some further investigation to examine the height loop tracker characteristics is advised.
In case C that is an analysis of one complete month of global SAR data we find evidence of about 0.015% of echoes of which about 0.007% are due to seasonal loss of track over the Arctic where the SIRAL-2 has failed to recognise loss of echo perform a transfer to acquisition mode.
By no means do we suggest by this analysis that our results are conclusive over all surfaces but for the cases examined in addition to those during commissioning we state the impacts of instrument saturation are negligible and can be identified and filtered if necessary. There is no evidence of ground processing saturation from the operational CryoSat processor products.

1.2 References

[R1] Saturation effects in the Seasat altimeter receiver, D. J. Wingham and C.G. Rapley, Int. Journal of Remote Sensing, 1987, Vol.8 No. 8, pp. 1163-1173.

[R2] Reduced SAR Techniques for CryoSat, R. Scharroo, W. Smith, E. Leuliette, J. Lillibridge, http://www.satoc.eu/projects/CP4O/docs/SARALT_EG_pdfs/Scharroo_CryoSat_RDSAR_Techniques.pdf

[R3] Blooms of σ^0 in the TOPEX Radar Altimeter Data, G. T. Michum, et al, Journal of Atmospheric and Oceanic Technology, Vol. 21, pp. 1232-1241.

[R4] A satellite altimeter model for ocean slick detection, J. Tournadre, et al, Journal, Geophys. Res., Vol. 111, doi:10.1029/2005JC003109, 2006.

2 ANALYSIS TO DETERMINE EXTENT OF INSTRUMENT SATURATION

2.1 Relevant CryoSat Requirements

The following text is taken from the CryoSat-2 Satellite Requirements Document. These requirements and echo test cases were verified by either review of design, analysis or test result.

Echo test cases:

For the derivation of the dynamic range of the instrument the Contractor shall assume the following echo shapes:

ocean echo (Brown echo);
ice echo 1, with a trailing edge slope of -0.125 dB/ns;
ice echo 2, with a trailing edge slope of -0.5 dB/ns;
ice echo 3, with a trailing edge slope yielding a total echo power equal to the total power of an ocean echo with a normalised backscatter coefficient (σ^0) of 40 dB. These shapes shall be assumed in the following ranges of σ^0:

In Low Resolution Mode:
- ocean echo for 6 dB < σ^0 < 25 dB
- ice echoes 1 and 2 for 0 dB < σ^0 < 40 dB

In SAR Mode:
- ocean echo for 6 dB < σ^0 < 25 dB
- ice echoes 1 and 2 for 6 dB < σ^0 < 25 dB
- ice echo 3 for 40 dB < σ^0 < 55 dB

In SARIn Mode:
- ocean echo for 6 dB < σ^0 < 25 dB
- ice echoes 1 and 2 for -10 dB < σ^0 < 40 dB

Note: If the surface characteristics are outside of these boundary conditions the instrument cannot be expected to function to its full performance. It is also worth noting that in general industry adds margins to such requirements.

General (all modes)
R-5.1.1.0.0-4 The gain of the receive chain shall be autonomously controlled to accommodate the full instantaneous dynamic range of the echo power.

SAR Mode specific:
R-5.2.3.0.0-5 Samples shall be coded with at least 16 bits per complex sample.
Note: This means 8 bits I and 8 bits Q. This level of precision is needed to avoid saturation.

SARin mode specific:
R-5.2.4.0.0-5 Samples shall be coded with at least 12 bits per complex sample.

Note: Again this means 6 bits I and 6 bits Q. The number of bits is less for SARIn Mode, which is unlikely to face the same dynamic range problem as introduced by the sea ice. Coding with 8 bits I and 8 bits Q is acceptable.

and also generally:
R-5.3.1.1.0-2 The receiver chain, including digital sections, shall accommodate a pulse-to-pulse variation in echo power of ±10 dB in the time domain.

2.2 Methods of determining instrument saturation

As mentioned at the NOC meeting (June 27th 2013), during commissioning a test was performed on SAR data acquired within the Arctic to assess if there were evidence of saturation and, if non-zero, whether the level was acceptable or not.
The method used for that study and what we have also adopted as a part of our analysis is to take the kurtosis of the I and the Q samples (separately). If the Kurtosis is <-1 (i.e., the distribution is Platykurtic, see Figure 1) then this was taken to be a potential case of saturation since it would indicate clipping of the I and Q samples, see Figure 2 as an example of simulated clipping. The commissioning study showed ~2.5% of data may be saturated over the Arctic. However, of those 2.5% no evidence of energy at spectral harmonics, see [R1], or 'ghosting' were seen[1]. The method of examining the Kurtosis alone fails if the echo is specular, see Figure 3. In this case the time-domain I and Q signal changes to a clearly defined sinusoidal shape and this changes the distribution of the samples and indeed the Kurtosis is <1. In other words, simply examining the Kurtosis provides an over-estimation of saturation. However, in our view, the analysis during commissioning showed a worse case level of saturation.

[1] If the I and Q data are clipped then signal energy at harmonic frequencies will occur. We refer to such signals as 'ghosts'.

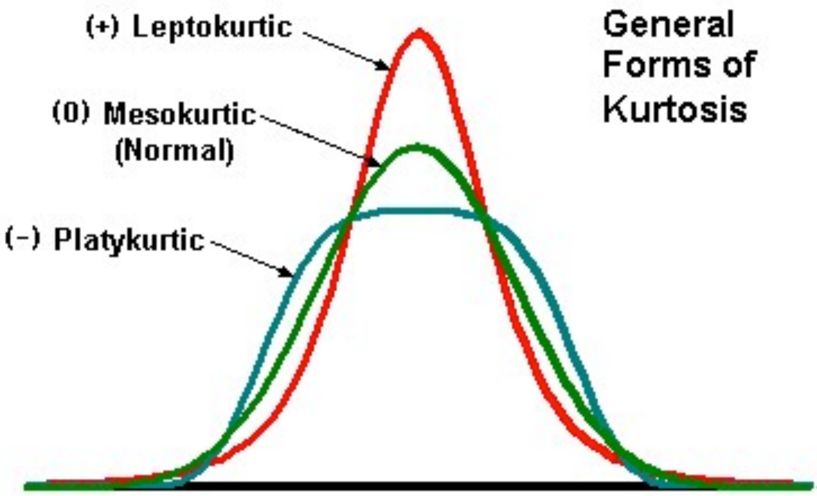


Figure 1 The three forms of distribution Kurtosis.

It has been explained to us by the instrument manufacturer[2] that for SAR mode any evidence of saturation will appear as clipped I and Q samples[3]. The figure below shows a simulation of this type of clipping with the impact on histograms from which the Kurtosis is derived.

[2] Thales Alenia Space, Toulouse, France.

[3] I or Q samples take values of -127 or +128 indicating saturation.

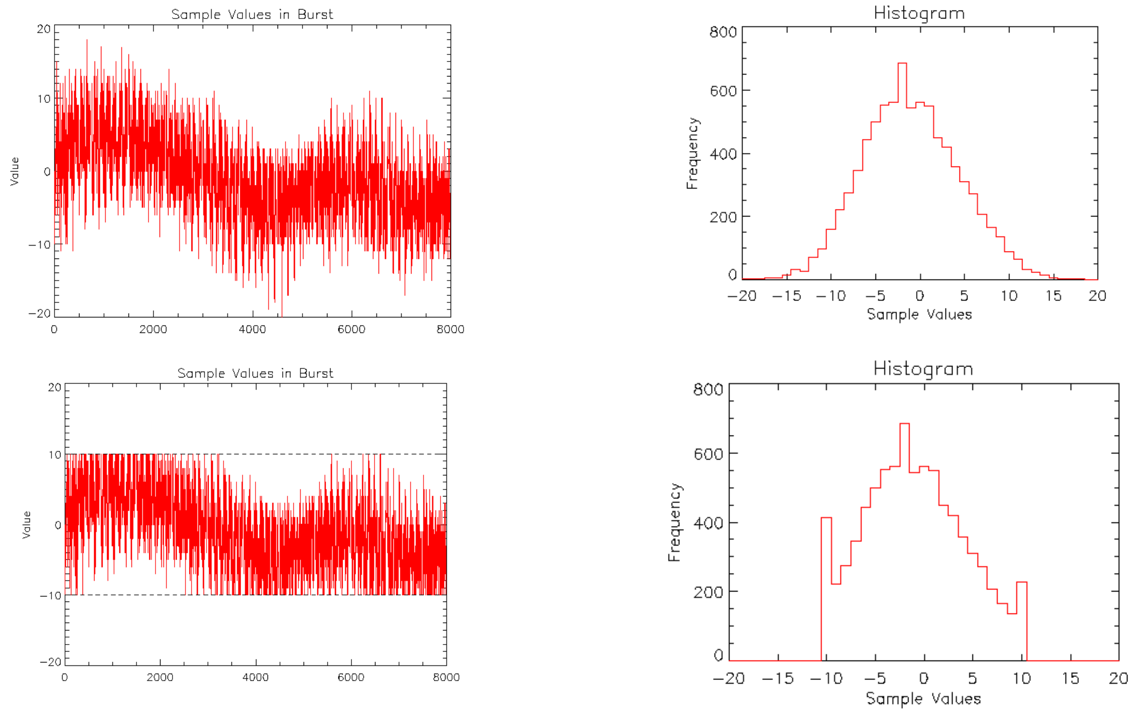


Figure 2 (Top left) Burst I samples for a non-saturated burst and (Top right) histogram that will have a kurtosis of ~0. (Bottom left) simulation of saturation with clipped samples value and (Bottom right) the associated histogram showing Platykurtic distribution and negative kurtosis.

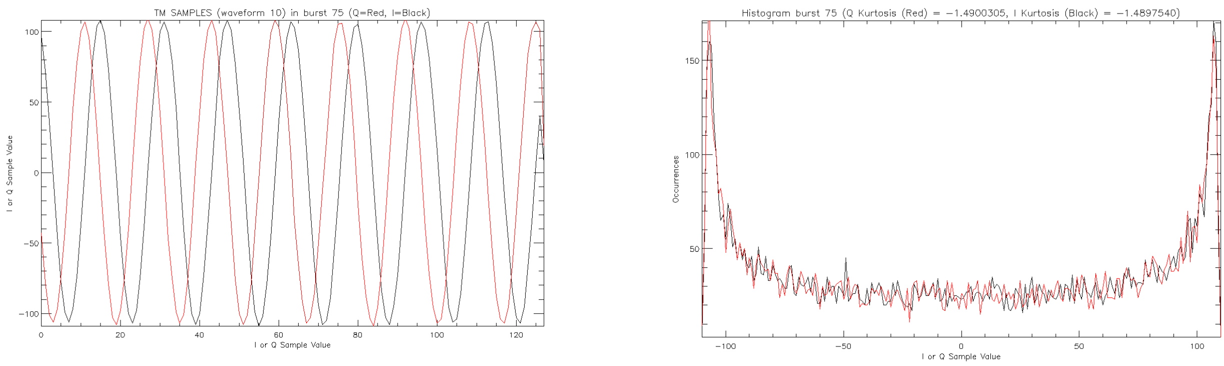


Figure 3 (Left) Non-Saturated I and Q samples (Case B FBR record 76) noting the available range is -127 to +128. (Right) the associated histogram. The peaks and troughs of the I/Q sinusoids result in the histogram have large number of counts at the sample value extremities and the Kurtosis is close to -1.5.

For the ESTEC analysis of case A and B we computed the Kurtosis for each burst in the profile and further looked at I and Q sample waveforms to assess if there is evidence of sample value clipping. In addition, we looked at the power level of the signal entering the instrument Digital Processing Unit (DPU) as derived from the I and Q data and assessed if it is has a mean of around -25dBm as per design since the instrument Automatic Gain Control (AGC) is computed in order to maintain the integrated power level of the signal entering the DPU to a fixed level with some tolerance (we would expect this to be around 1dB for ocean). We have generated pulse-width limited echoes (range compression FFT applied to the I and Q echoes followed by square law detection to obtain a power echo and

averaged over a burst) to assess if there is harmonic ghosting due to the squaring off of the waveforms. Finally, we have analysed the level 1b power echo waveforms.
For SAR tracking and LRM echoes we further look at the distribution of integrated power. This analysis is incomplete at the time of writing. Industry are looking into this particular case though it will take some time to report on it.

2.3 Analysis cases

2.3.1 Case A1: Flat Sea Effect – SAR

FBR File: CS_OFFL_SIR1SAR_FR_20120521T180411_20120521T180629_B001.DBL

The following case has been provided by Walter Smith and contains two parts. 1. SAR (see Figure 4) over a FSE scenario and 2. LRM data, Figure 5. The retrievals that demonstrate the existence of the FSE are also provided in Figure 5 (presented at NOC, [R2]) based on pulse-width limited power echoes generated from the SAR FBR burst echoes. One can observe the σ^0 increases from the value of ~15 dB and goes off scale in Walter's plot but not outside the specification (LRM/SAR ocean Brown echoes 6 dB < σ^0 < 25 dB) and hence the instrument should be able to handle the variation in returned power. The first point to note is that the waveforms display no obvious sign of energy at harmonics, see [R1], that would indicate clipping of the I and Q.

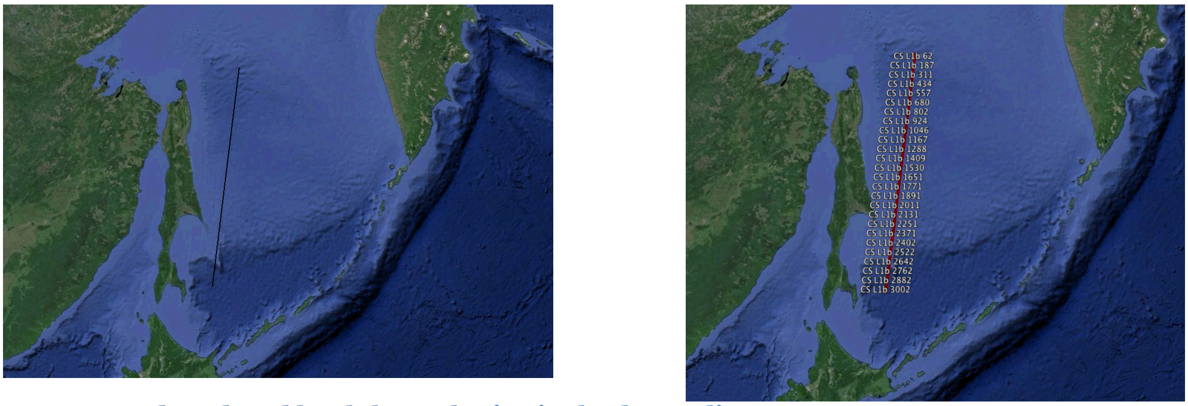


Figure 4 Ground track and level 1b numbering in the descending pass.

The returned power (after application of the AGC), however, increases as observed in σ^0 but it is not fully understood how this has been generated (I come back to this point later).

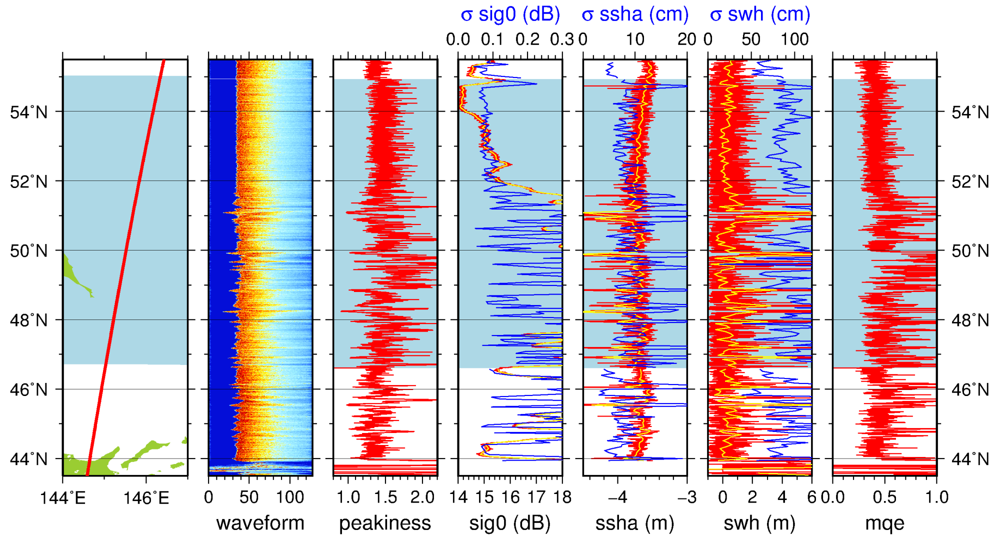
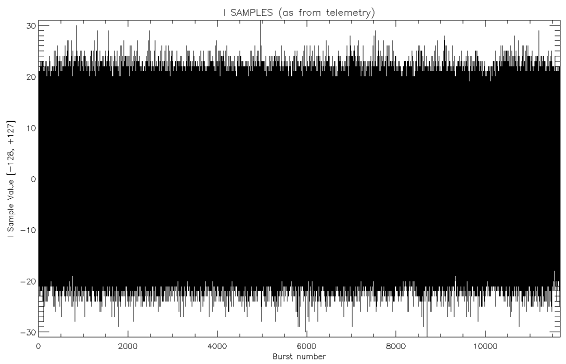
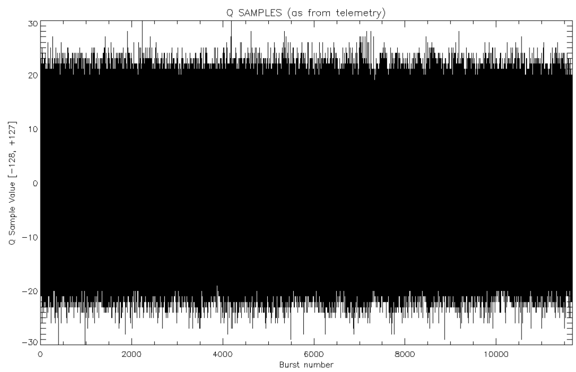


Figure 5 Plot provided by Walter Smith (from [R2]) showing (left) the ground track with the radar operating in SAR in grey and LRM in white. Pulse-width limited power waveforms from the radar (LRM) and derived from FBR in SAR (i.e., no SAR processing). Peakiness using a standard algorithm (TBC), σ o (derivation TBD), Sea surface height anomaly (derivation TBD), Significant Wave Height (derivation TBD). MQE (meaning TBC)

Figure 6 provides a plot of the SAR I and Q samples (note the samples can hold values between -127 and +128), the histogram of samples are shown more or less to be Gaussian and the Kurtosis showing the average distribution is very slightly Leptokurtic for each burst and therefore not quite Gaussian. From this data there is no evidence the data are saturated for any of the bursts over the full profile.

Moving onto the power of the signal entering the DPU, see Figure 7, the instrument is operating per design and maintaining the signal level into the DPU with a standard deviation of ~0.7dB. Over the areas of ocean the instrument varies the AGC to keep the signal into the sensitive digital hardware (DPU) at a level to avoid damage whilst still respecting the need to adapt to a rapid change in signal power as demanded over sea ice and leads between the sea-ice floes.





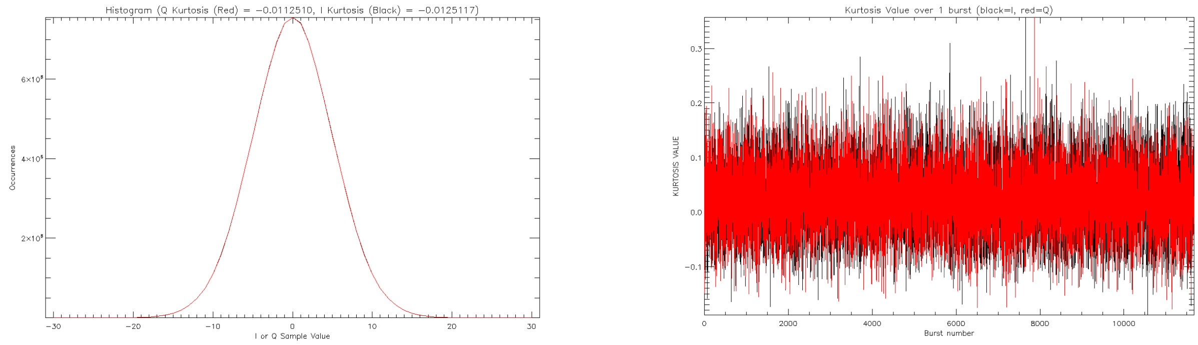


Figure 6 (Top left) I samples over the full FSE profile (Top right) Q samples over the full FSE. Note the available range is -127 to +128. (Bottom left) The histogram of sample counts and (Bottom right) the Kurtosis over the full profile. This result categorically shows that the Automatic Gain Control (AGC) loop is functioning to specification based SAR tracking echoes that are produced on-board.

The level 1b data are plotted as a z-scope in Figure 8. As one would expect in the SAR processing the normalised power echoes show nothing particularly odd.

Also provided in Figure 8 is a z-scope of the power echoes after application of the power scaling factors and plotted with respect to the peak power of the full profile (around 49.8° latitude). Here one can see the impacts of the FSE on the SAR processed echoes (unlike the pulse-width limited processing in Figure 5). Based on the colour table used one case see the echo shape changes with latitude. It is unclear how the σ^0 in Figure 5 ties in with the L1b SAR echoes.

Referring back to [R2], slide 14 states 'Tracker often goes haywire'. The instrument operation is rather simple. Over 'normal' ocean surfaces the pulse-width echo shape approximates to the Brown echo shape, however, if the surface within the pulse-width limited footprint is affected partly by oil or some biological substance then parts of the pulse-width limited footprint will provide specular or quasi specular returns which result in echos no-longer being Brown like (just like echo returns in the Arctic sea ice and the reason to design CryoSat to improve the along-track resolution). This type of effect is very well demonstrated in the paper by Tournadre et al, [R4].

The instrument on-board tracking height loop for SAR and LRM modes is the 'Median' tracker as used on Jason-1 and 2 (earliest detectable part for SARIn) with a different tuning, if the echo shape is varying the instrument thinks there is a height rate associated with surface topography and derives a height rate for the next tracking cycle. This can result in some blurring of the pulse-width limited echo in LRM and SAR (the SAR tracking echo). In principle one could re-tune the on-board tracking to make it less sensitive, however, it is tuned for it's primary mission and there is no need to re-tune without potential side effects. The statement on slide 14 of [R2] would be more appropriately re-stated as 'instrument response on non Brown-like echoes'.

It should be noted that with an on-board along-track elevation model that is provided for Jason-2, 3, CS and Sentinel-3 (the so called OLTC[4]) this form of problem is most likely to be minimised, noting the in-orbit Jason-2 does not operationally use this facility.

If the CS-2 SAR data are actually SAR processed then this issue is also somewhat alleviated, though one has to recognise that in the across track the data are still pulse-width

[4] OLTC – Open loop tracking command

limited, though the impact is somewhat reduced as shown in Figure 8. There are enough parameters available in the L1b product to filter data impacted by this phenomena in LRM and SAR.

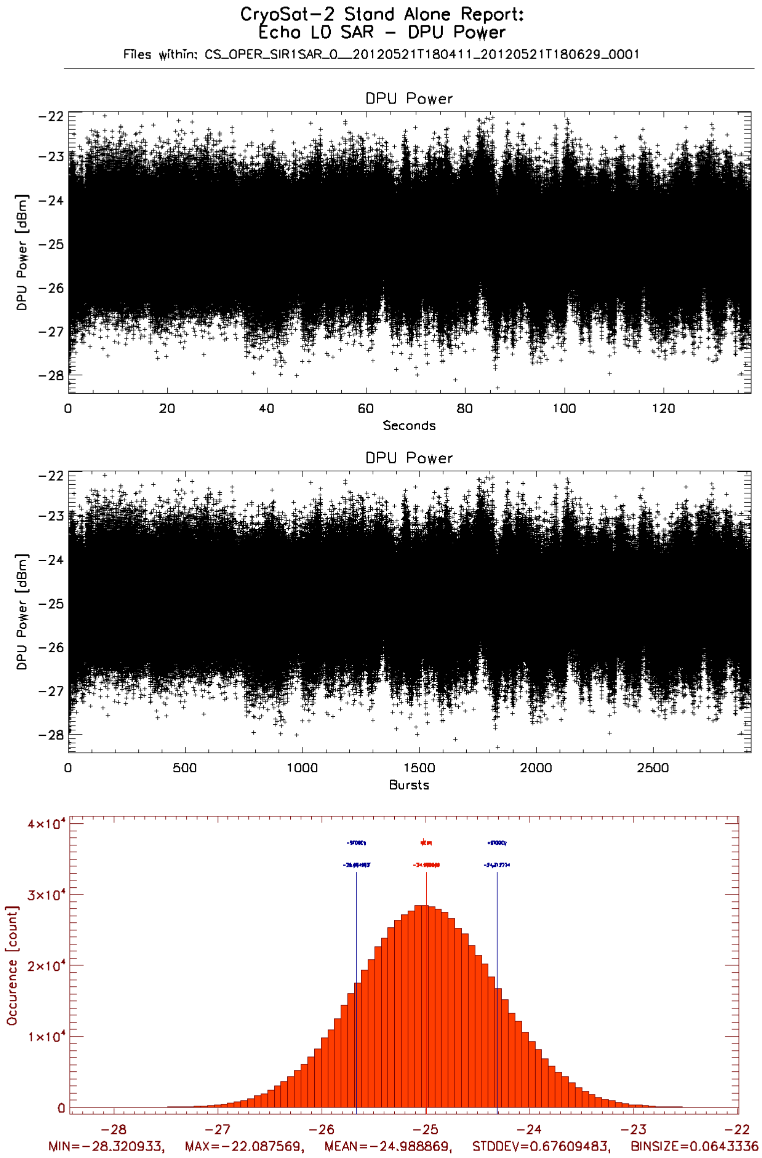


Figure 7 Power level of signal entering the DPU for the FSE SAR case. (Top) Signal power level as a function of the ~140 seconds of the recorded data (Middle) as a function of the burst and (bottom) a histogram for the full period including regions displaying the FSE.

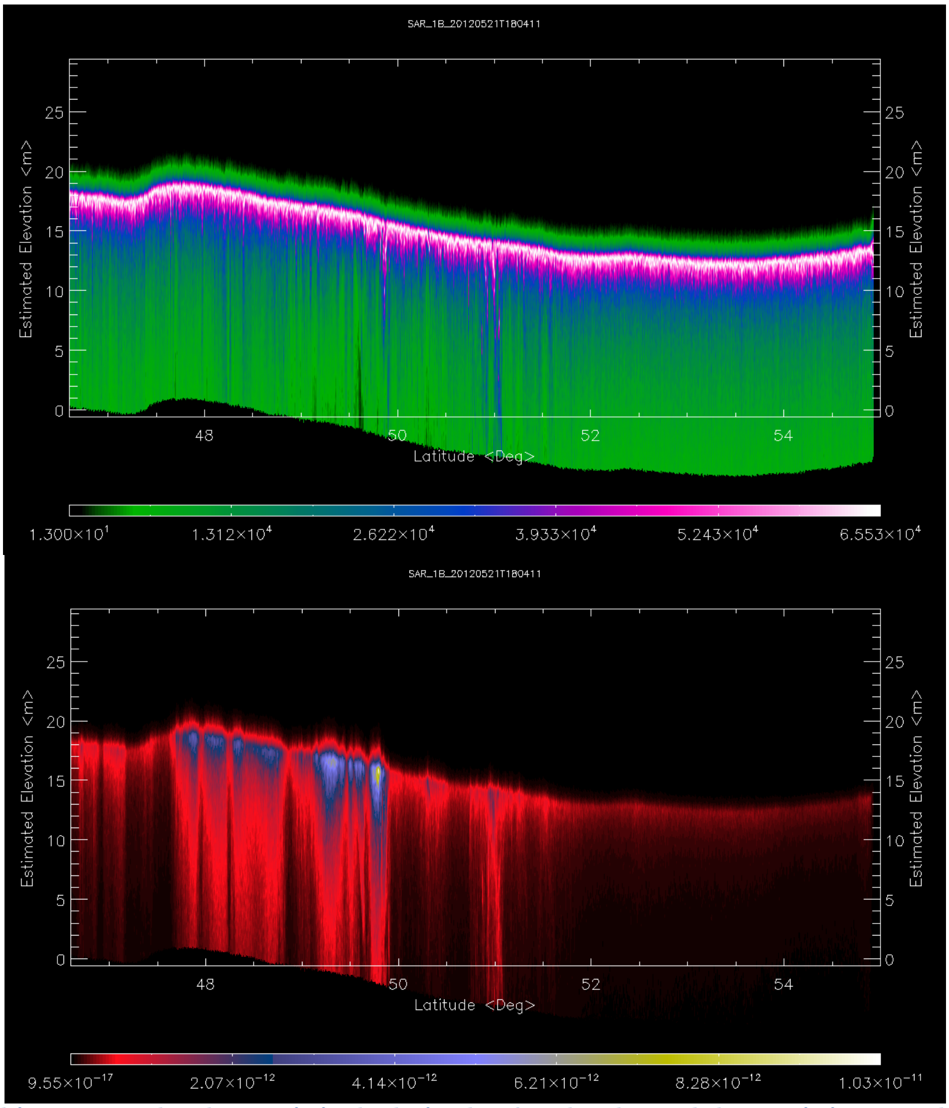


Figure 8 For this z-scope plot the x-axis is the latitude of each echo and the y-axis is termed incorrectly as 'estimated elevation'. What this means is each L1b waveform is simply shifted with respect to the orbit height and window delay (range) to derive an estimated elevation for the centre of the echo window. All other samples are plotted with respect to the echo window centre and thus energy that appears as a lower elevation than the leading edge of the waveform is simply further in range. No geo-corrections have been applied. This type of plot provides (Top) Normalised Level 1b power echoes (each power echo sampled is normalised with respect to the echo peak power of that echo). (Bottom) Level 1b scaled power echoes with the colour table peak power being that of the peak power of the full profile (~49.8°). Although the source data are the same the method of display provide quite different results.

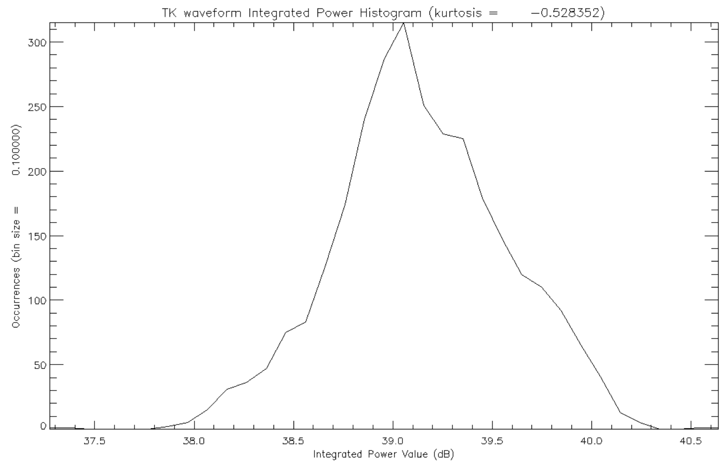


Figure 9 Histogram of SAR tracking echo integrated power. There is nothing odd with this plot though further investigation is needed as to specific instrument operation.

Conclusion: There is no evidence of saturation of the instrument over regions displaying FSE. The on-board AGC loop is behaving as expected maintaining the power entering the DPU at a fixed level with an acceptable standard deviation of about 0.7 dB.

2.3.2 Case A2: – Flat Sea Effect – LRM

To be added: However, the effect is described in §2.3.1

2.3.3 Case B: Caspian Sea and Volga River Delta (inland)

FBR file: CS_OFFL_SIR1SAR_FR_20120806T204037_20120806T204125_B001.DBL

This descending pass profile is over the inland river Volga Delta onto coastal and open Caspian sea, see Figure 10. Examination of the Kurtosis of the burst I/Q data show over the Caspian Sea the distribution has a distribution that is slightly Leptokurtic, Figure 11. Over the inland regions there are large negative value of Kurtosis that we investigated further. Examination of these bursts show a single case (burst) of saturation at FBR record 31, Figure 13, where the surface changes very quickly from land to a small region of (assumed) very calm water (according to an image from Google Earth, Figure 14). The radar operates by fixing the AGC for radar cycles (~50ms in length) that cover four bursts. If the instrument is tracking land and the AGC loop is maintaining the power level into the DPU at a fixed level (meaning high gain) and then the return instantly changes from diffuse to specular then saturation can occur, however, the dynamic range of the receiver is sufficiently large to handle large variations in backscatter by definition of the primary sea-

ice mission objectives. Without knowledge of the backscatter characteristics of the land and lake/water we cannot investigate further.
The bursts 30 and 32 display less specular echoes and it is simply the 'flash' from the lake that is causing the instrument to briefly saturate. The instrument is somewhat close to saturation for a few bursts around record 76 under similar conditions of dynamic backscatter changes.
Despite this example being over inland water (and not coast, nor ocean, nor the mission defined surfaces) the SIRAL-2 is functioning remarkably well over the widely variable surface with large dynamic σ0 variation.
We performed a further test on the power variation into the DPU, see Figure 15, and see the mean power level is as expected though the spread is larger. If the plot were split into surface type it would provide a better demonstration on the power variability over land and wetlands opposed to the ocean that is very stable.

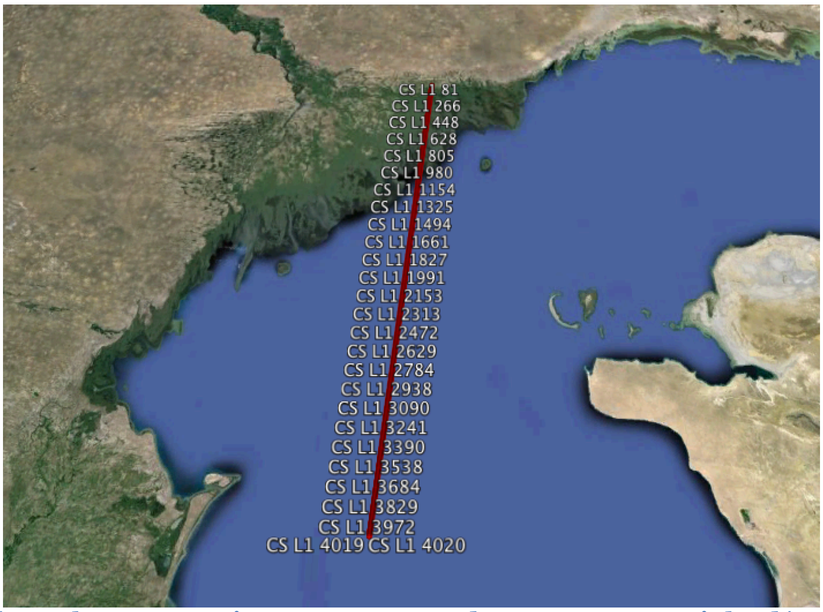


Figure 10 River Volga Delta onto Caspian Sea: FBR records: 1 to ~980 cover inland/wetland area.

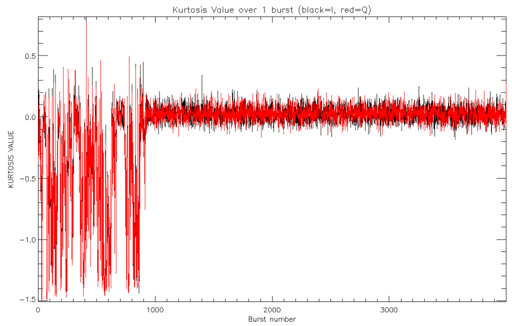


Figure 11 Kurtosis of bursts of I/Q samples over the inland River Volga Delta (Bursts 0-~1000) onto the Caspian sea. As expected the latter are almost Gaussian over the ocean. Over inland water there is evidence of saturation in a single burst (FBR record 31), all other cases are specular returns.

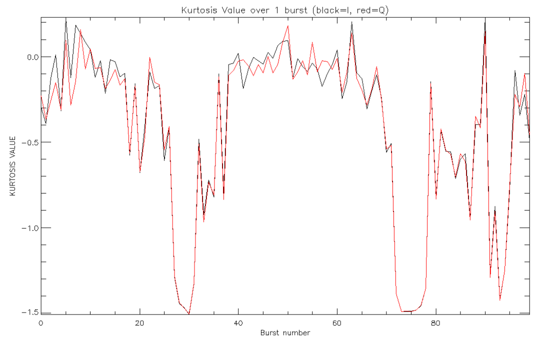


Figure 12 Kurtosis over first 100 bursts. Saturation occurs at burst 30 (FBR record 31). The few bursts around 75 are close to saturation.

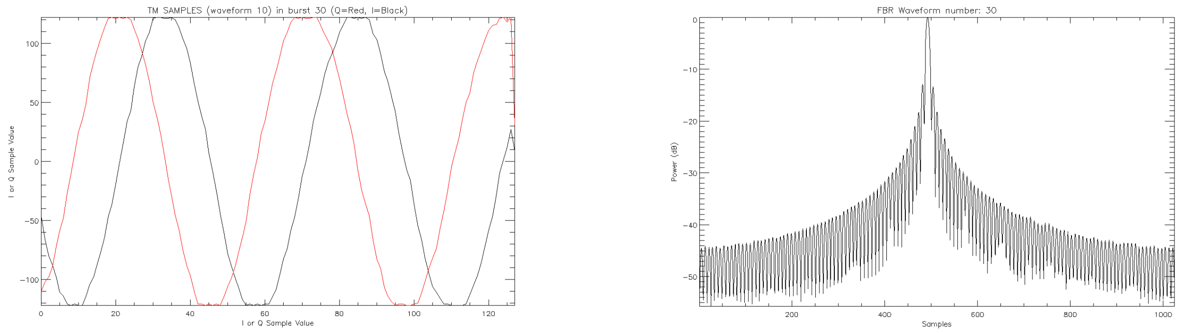


Figure 13 (Left) FBR record 31 (burst 30 in plot) displaying the one case of echo clipping and (right) the impact on the range compressed normalised power echo is negligible. Harmonics signals at 40dB below the peak power can be observed if a Hamming window is applied.

Figure 14 (Left) Level 1b records and locations at which burst azimuth beams are steered. (Right) The apparent lake (some 600 meters in length and 60 meters in width at the ground track intersection. Level 1b records (labelled CS2 Rec X) and FBR Burst (labelled CS L1 XX, where XX is the record number) locations are shown. The FBR burst that is saturated is record 31. The impact of a saturated burst on level 1b can cover 64 level 1b echoes.

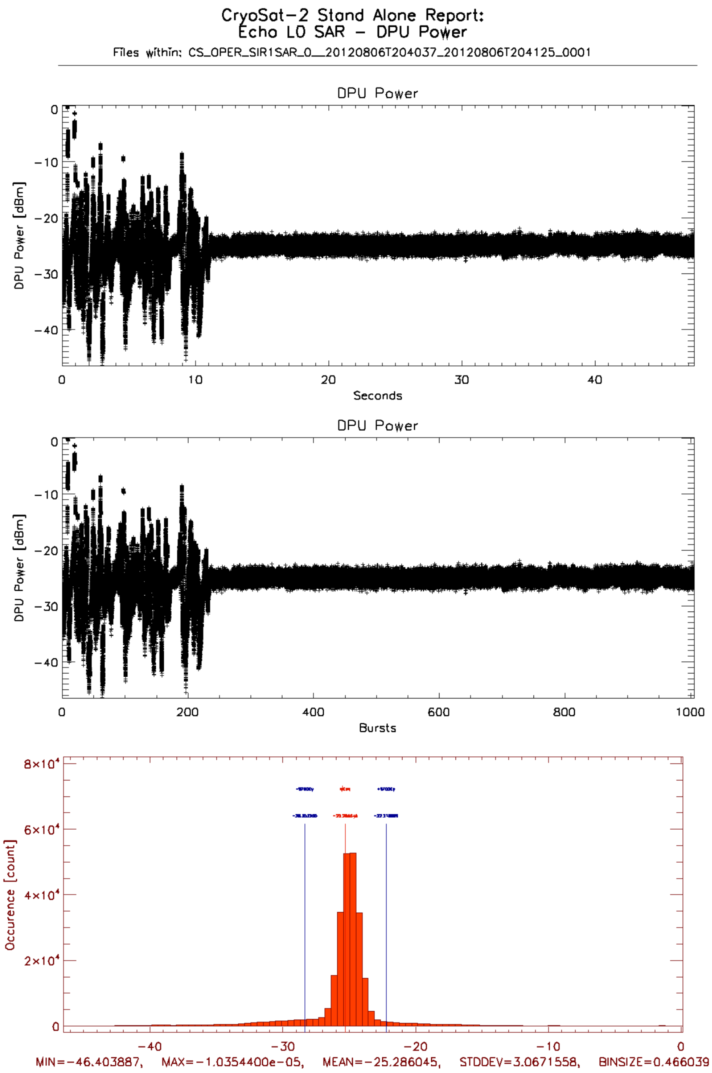


Figure 15 Power level of signal entering the DPU for the FSE SAR case. (Top) Signal power level as a function of the ~50 seconds of the recorded data (Middle) as a function of the burst and (bottom) a histogram for the full period including the wetland area and ocean.

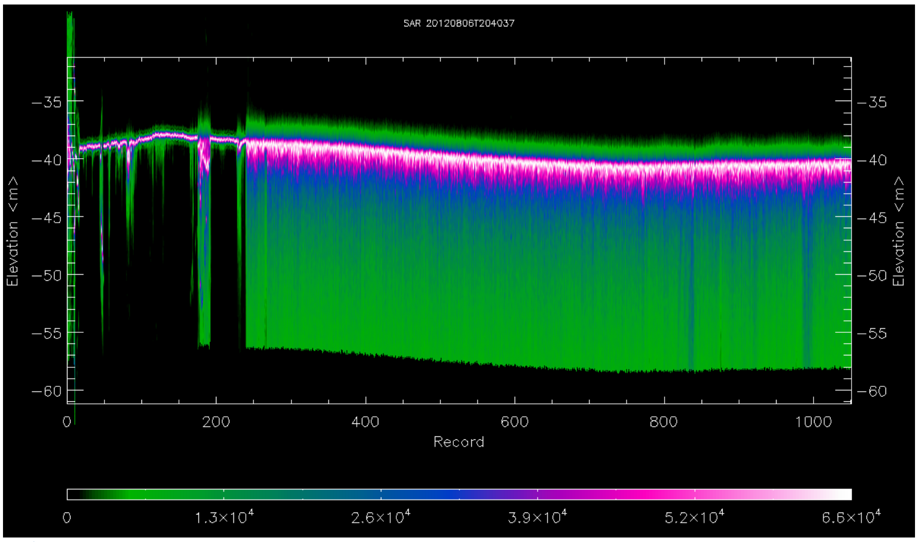


Figure 16 Normalised Level 1b power echoes.

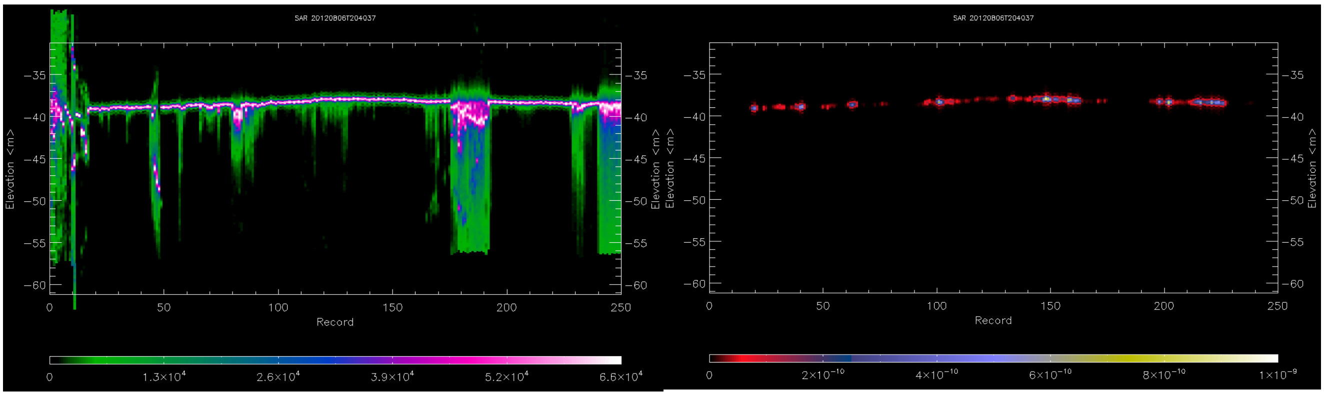


Figure 17 (Left) Normalised Level 1b power echoes aligned with window delay. It should be noted the first 31 echoes are composed of incomplete stacks since the start of SAR acquisition (record 1) will only contain a half stack (~120 echoes) and this builds up to a complete stack by record 31. This type of result is not dissimilar from those sea ice (Right) Level 1b individually scaled power echoes.

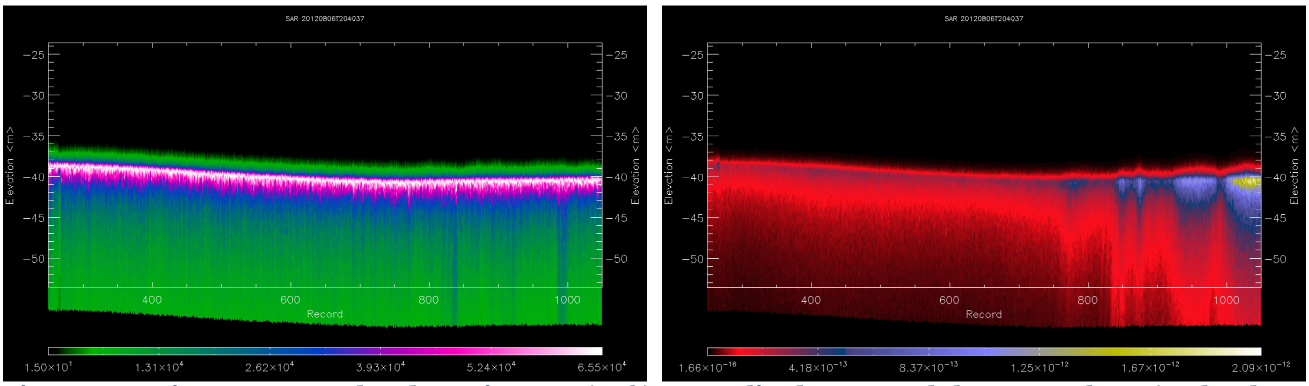


Figure 18 Region over coastal and Caspian sea. (Left) Normalised SAR Level 1b power echoes (each echo normalised to its maximum value). (Right) Scaled level 1b power echoes indicating echo shape change.

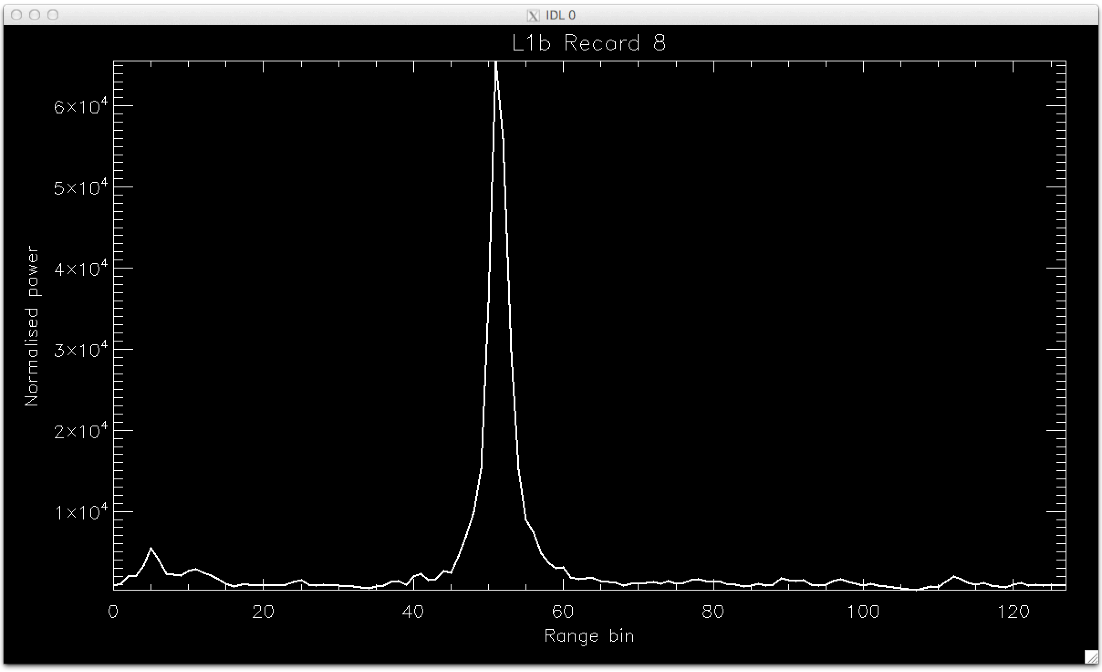


Figure 19 Level 1b power echo record 8. The saturation of FBR record 31 has an impact on L1b echoes 1 to 31 due to beam formation. However, the main impact will be on L1b record 8 due to antenna pattern amplitude modulation being at its lowest. Although this echo is by no means perfect it is difficult to comment on it without knowledge of the surface.

2.3.4 Case C: One Month (June 2013) SAR Level 0

Based on the knowledge that saturation is observed when I or Q values are clipped at either values of -127 or +128, one complete month of SAR Level 0 each echo were examined.
In total 0.014% were seen to saturate. These are mainly over inland regions as can be seen in Figure 20. In the lower panel of Figure 20 it can be seen that there are many bursts (seen as lines) that are indicated as saturated that have been observed over previous Arctic summer seasons since launch (April 2010) with several brief occurrences per month that reduce to zero following the freeze-up period. Here the instrument is tracking cloud rather than the underlying surface as the platform passes from land to Arctic ocean and fails to transfer to acquisition mode. Nevertheless, mission objectives for sea ice thickness retrieval are not impacted. The instrument is in this state of failing to track properly for about 0.006% of the time for this particular data set. During the Arctic winters (for which the mission is design to retrieve seasonal thickness) this phenomenon does not occur.

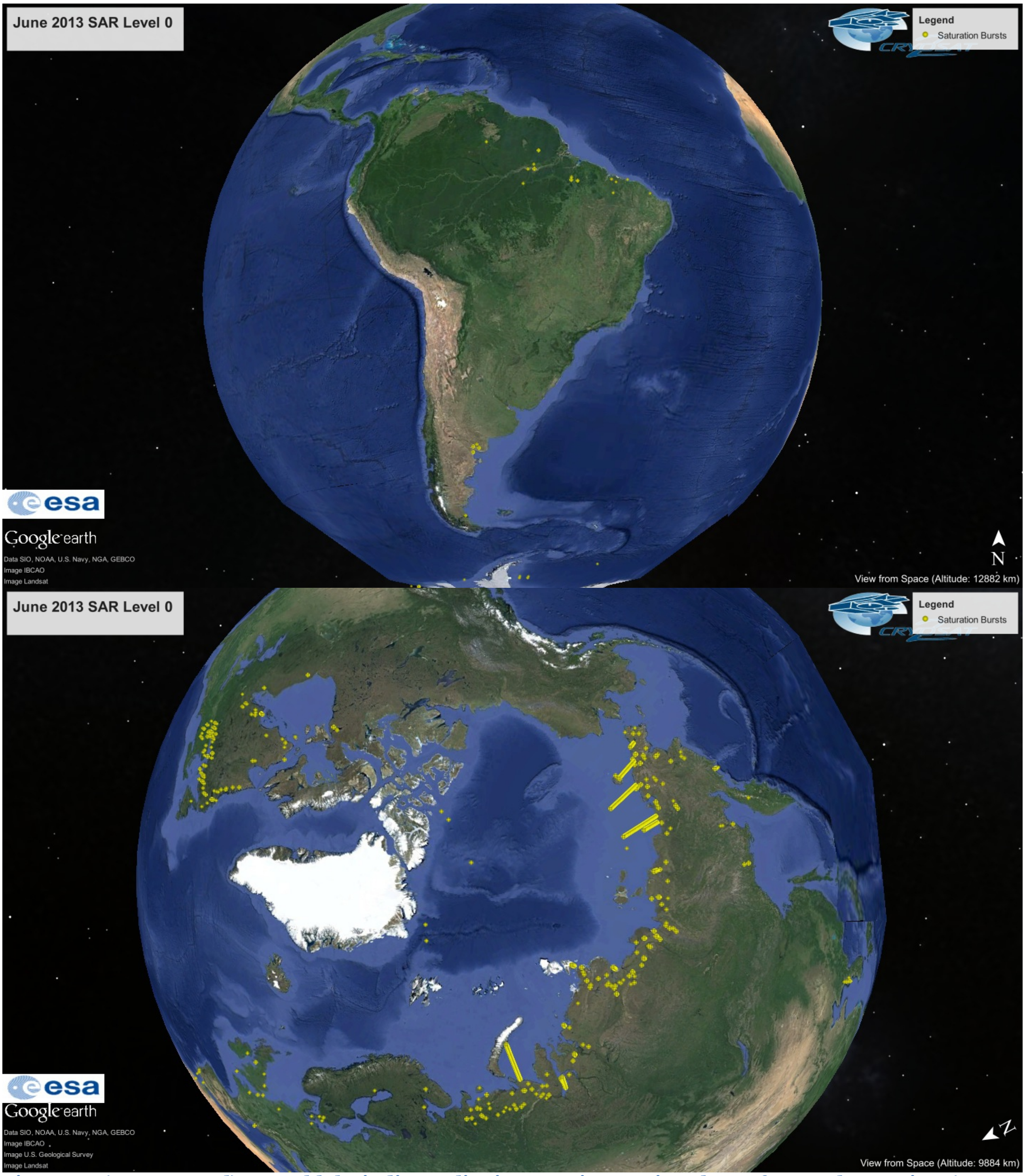


Figure 20 (Upper panel) green blobs indicate clipping seen in any given burst for South America. (Lower panel) saturation indicated over the Arctic mainly inland. See text as to the reason for the several profiles displaying apparent saturation. The overall percentage of echoes that appear saturated during June 2013 is 0.014%.

2.3.5 *Case D: SAR Tracking echoes*

To be added.

3 CONCLUSION

There is no evidence of saturation of the SIRAL-2 receiver that impacts the mission objectives.

I would like to thank Andy Ridout (UCL) for the use of Figure 1 and Figure 2, Walter Smith and Remko Scharoo for Figure 5 and Marco Fornari (ESA) for Figures 7,11,12,13 and 15.