ABSTRACT
It has been demonstrated that for the proper exploitation for the S-Band data, a calibration is required. Pildo Labs, IsardSAT and UCL are presenting here a cross-calibration of the S-band range against the Ku-band range, performed by comparing the S-band echoes against the Ku-band echoes over the salar Uyuni. This target has been chosen because of the very special nature of its return echo. A retracker suitable for the Uyuni echoes has also been developed.

1. INTRODUCTION
In order to exploit the S-band data, a calibration is required. If we are to obtain scientific results from the RA-2 S-band, we have to relay on its measurements and in particular the range measurement. And the only way to do that is by having a calibration of the S-band range measurement.

Investigations of the RA-2 data [1] show that the height differences between the Ku- and S-bands, range from negative (-1 meter) to positive (+1 meter). A similar phenomenon is observed for comparisons over sea ice, where the S-band elevations are seen to lie consistently above those for Ku. This is physically not possible, and the only way to de-couple what is caused by a physical effect or by an error in the range measurement is by performing a calibration of both the Ku and S-band range measurements.

Pildo Labs, IsardSAT and Seymour Laxon are presenting here a cross-calibration of the S-band against the Ku-band. This calibration has been performed by comparing the S-band echoes against the Ku-band echoes over the salar Uyuni, because of the very specular nature of the salar returns. The study has been performed with Level 1b data, using the average waveforms but also including Individual echoes. In order to retrieve the point of return a retracker suitable for the Uyuni echoes has also been developed. The geophysical corrections that need to be applied are only the ones that affect differently the Ku and the S-bands ranges. This is the ionospheric correction. The model used for such purposes is the GIM model developed at JPL. We have also assessed the errors due to inaccuracy of this correction.

2. RANGE COMPUTATION
In order to calculate the range measured by RA-2, which is the distance between the altimeter and the Salar surface, we need to add the delay of the range window, together with the position of the echo within the window. For that purpose we will retrack the waveforms provided by the instrument when over flying the Salar, in order to calculate the position of the received signal. Since the Salar response is a point target, the response is a very narrow echo that covers only a few samples. The position of the Salar corresponds to the position of the maximum of the waveform. This maximum provides us with the delta range that shall be added to the window delay, extracted from the Level 1b product. Furthermore, this range will be corrected by the ionospheric delay.

The range has been computed as in the RA-2 Level 2 products (described in the RA-2 Level 2 DPM):

- Range computation for Ku band:
  \[ tmp\_range = \left( windel_s - 63 \cdot \frac{1}{Bw_r} \right) \cdot \frac{c}{2} \]  
  \[ range_s = tmp\_range + gauss\_centre \cdot \sqrt{Bw_c} \cdot \frac{c}{2} \]  
  Eq. 1
  Eq. 2

- Range computation for S band:
  \[ tmp\_range = \left( windel_s - 31 \cdot \frac{1}{Bw_s} \right) \cdot \frac{c}{2} \]  
  \[ range_s = tmp\_range + gauss\_centre \cdot \sqrt{Bw_s} \cdot \frac{c}{2} \]  
  Eq. 3
  Eq. 4

3. RETRACKER
In order to determine the maximum of the waveform in an accurate way we need to develop a retracker. The retracker is applied to both the Ku- and S-band

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ENVISAT RA-2 S-BAND RANGE CALIBRATION VERSUS KU-BAND RANGE, OVER THE SALAR DE UYUNI
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waveforms.

Three possible retrackers have been considered:
- a Gaussian retracker: fitting with a Gaussian function
- a zero-padding retracker (also called sinc-convolution), equivalent to perform a Gaussian interpolation
- a zero-padding + Gaussian retracker

- **The Gaussian retracker**

The Gaussian retracker is the simplest one. It computes the coefficients of a Gaussian equation (Eq 5) that better fits with the given waveform.

\[ y = x_0(1) \cdot e^{-\left(\frac{x}{\Delta}\right)^2} \cdot \frac{x}{\Delta^2} \]  
**Eq. 5**

An example can be found in Figure 1, where the blue line is the original waveform taken from the Level 1B and the green line is the output of the Gaussian retracker, which follows Eq 5.

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**Figure 1. Gaussian retracker**

- **The zero-padding retracker**

The zero-padding consists on adding zeros to the waveform between samples, similar to an interpolation. The objective of the addition of zeros is to increase the number of samples and consequently to obtain the position of the maximum of the waveform with a better precision.

- **The zero-padding + Gaussian fitting retracker**

Figure 2 shows the steps followed by the retracker:
1. The original waveform with only 3 important points.
2. The same echo after Zero-padding
3. And finally, the last figure shows, in green, the echo after zero-padding and Gaussian fitting (the Gaussian fitting only applied over the main lobe of the sinc).

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**Figure 2. Retracker over the L1b echo**

Data have been processed with the three retrackers. To evaluate the noise of the retrackers, we performed the standard deviation of the position of the maximum after having run the retracker. However, selection of the best retracker was not possible by only visual inspection. For that purpose we performed an Analysis of Variance test (ANOVA) (see [2]).
3.1 ANOVA (ANalysis of VAriance between groups)

Analysis of variance (ANOVA) is used to test hypotheses about differences between two or more means for significance. Significance tests are performed to see if the null hypothesis can be rejected. If the test is significant, then the null hypothesis is rejected and the effect found in a sample is said to be statistically significant (it can be concluded that there is an effect). If the null hypothesis is not rejected, then the effect is not significant.

The comparison between the actual variation of the group averages and that expected is expressed in terms of the $F$ ratio:

$$F = \frac{\text{found variation of the group averages}}{\text{expected variation of the group averages}}$$

The numerator and denominator of $F$ are computed following the next steps:

- Numerator: Found variation of the group averages = sum of squares between groups/degrees of freedom between-groups
- Denominator: Expected variation of the group averages = sum of squares within groups/degrees of freedom within-groups

This $F$ is compared with the tabulated values of $F$ (see [3]).

To see if the null hypotheses can be rejected or not, we have computed the $F$ ratio for the available tracks over the Salar for the year 2005. Waveforms analysed correspond exclusively to the Salar. The $F$’s are shown in the table below (Table 1):

<table>
<thead>
<tr>
<th>Track over the salar</th>
<th>$F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>27 January 2005</td>
<td>0.4737</td>
</tr>
<tr>
<td>3 March 2005</td>
<td>0.1109</td>
</tr>
<tr>
<td>4 March 2005</td>
<td>0.1579</td>
</tr>
<tr>
<td>12 May 2005</td>
<td>1.466</td>
</tr>
<tr>
<td>13 May 2005</td>
<td>0.0029</td>
</tr>
<tr>
<td>16 June 2005</td>
<td>0.0119</td>
</tr>
<tr>
<td>17 June 2005</td>
<td>0.0275</td>
</tr>
<tr>
<td>21 July 2005</td>
<td>0.1387</td>
</tr>
<tr>
<td>22 July 2005</td>
<td>0.1380</td>
</tr>
<tr>
<td>25 August 2005</td>
<td>0.1221</td>
</tr>
<tr>
<td>26 August 2005</td>
<td>0.0208</td>
</tr>
</tbody>
</table>

The expected tabulated value of $F$ is 3.01 (see [3]). From Table 1, the highest computed $F$ is smaller than 1.5 (12 of May 2005). As the computed $F$’s are smaller than the expected one, the null hypothesis is correct.

As a result of the ANOVA analysis we can confirm that none of the 3 retrackers is better than the others. That’s why, we will compute the ranges using the three retrackers and will select the less noisy one.

4. IONOSPHERE

A critical issue in the cross-calibration of the RA-2 Ku- and S-band range measurements is the availability of an independent model estimate for the ionospheric correction. Further it must also be possible to estimate the error in this model correction to assess its impact on the cross-calibration. The best method of achieving this is to compare the modelled correction with that computed from the difference in Ku- and S-Band ranges, the so called RA2 ionospheric correction. Unfortunately for the RA-2 this correction itself is compromised by the fact that the S-band range has not been calibrated. However a first estimate of the model ionospheric correction can be obtained using independent observations particularly from TOPEX.

Figure 3 shows a comparison between a number of different model ionospheric corrections including the JPL GIM model used in this study.
of the correction. (a) Delays along Passes 123 and 124 of TOPEX Cycle 348 (28 February 2002). (b) Cycle-by-cycle mean differences between modelled and dual-frequency delay (September 1998 to June 2002) [Scharroo, 2002]

The comparison between the GIM model and TOPEX ionospheric correction shows that, overall, the nighttime correction is accurate to 1-2 cm although the daytime corrections show rather larger excursions, of up to 10 cm at certain latitudes. It is possible therefore that a significant fraction, but by no means all, of the difference between the S- and Ku-band ranges on the ascending and descending passes are due to errors in the GIM model. Further investigations with the RA-2 data will shed light on this matter.

5. RESULTS WITH LEVEL 1B AVERAGED DATA

Envisat flies over the Uyuni Salar on tracks 139 (descending) and 146 (ascending), thus these are the tracks analysed in this report.

After processing the data with the different retrackers, it was seen that the ranges obtained with the Gaussian retracker were much smoother than the others. That’s why the Gaussian retracker was selected for the S-band calibration.

Figure 4 and Figure 5 show the differences between the Ku-band and S-band ranges for the descending track 139 and the ascending track 146 respectively. These ranges have been previously corrected by the ionospheric effect provided by the GIM model. Each month is presented with a different colour. The horizontal axis is the latitude and the vertical axis is the difference of ranges between both bands given in centimetres.

![Figure 4](image.png)

**Figure 4. Difference between the Ku-band and the S-band ranges, by month (Descending Track)**

The difference between ranges are more spread than expected, which is due to the ionospheric correction, as seen in section 4.

Table 2 shows the range comparison obtained by computing the bias that minimises the \( \text{rms} \) between the two ranges, as:

\[
\frac{\partial}{\partial \text{bias}} \left[ \frac{1}{N} \sum_{i=1}^{N} \left( r_{\text{Ku}}(i) - (r_{\text{S}}(i) + \text{bias}) \right)^2 \right] = 0 \quad \text{Eq. 6}
\]

The high standard deviations confirm that the differences in ranges are very spread.

<table>
<thead>
<tr>
<th>Date</th>
<th>Descending (139)</th>
<th>Ascending (146)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mar’05</td>
<td>12.8 cm</td>
<td>-1.9 cm</td>
</tr>
<tr>
<td>Apr’05</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>May’05</td>
<td>7.8 cm</td>
<td>7.86 cm</td>
</tr>
<tr>
<td>June’05</td>
<td>17.0 cm</td>
<td>-3.2 cm</td>
</tr>
<tr>
<td>July’05</td>
<td>9.1 cm</td>
<td>2.78 cm</td>
</tr>
<tr>
<td>Aug’05</td>
<td>-0.9 cm</td>
<td>-22.32 cm</td>
</tr>
<tr>
<td>Sept’05</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Oct’05</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Nov’05</td>
<td>14.7 cm</td>
<td>1.68 cm</td>
</tr>
<tr>
<td>Dec’05</td>
<td>15.4 cm</td>
<td>21.6 cm</td>
</tr>
<tr>
<td>Jan’06</td>
<td>17.1 cm</td>
<td>19.1 cm</td>
</tr>
<tr>
<td>Feb’06</td>
<td>17.9 cm</td>
<td>-12.8 cm</td>
</tr>
<tr>
<td>Mar’06</td>
<td>-4.9 cm</td>
<td>15.7 cm</td>
</tr>
<tr>
<td>Apr’06</td>
<td>5.8 cm</td>
<td>3.0 cm</td>
</tr>
<tr>
<td>July’06</td>
<td>8.5 cm</td>
<td>9.6 cm</td>
</tr>
</tbody>
</table>
As we have seen in Section 4, the GIM model and the DORIS ionospheric corrections present differences of some centimetres. In order to see if the results improve with the DORIS ionospheric correction, we have recomputed the Ku-S band range difference after correcting the range with the DORIS iono. However, as seen in Figure 6, the differences are much more spread than when using the GIM model.

These differences are of the same order of magnitude than the difference between DORIS and GIM ionospheric corrections, which are about +/-30 cm (Figure 7). Therefore, we can not obtain the error of the S-band over the Ku-band if the ionospheric corrections are not previously validated.

6. RESULTS WITH LEVEL 1B INDIVIDUAL ECHOES

One Level 1B averaged waveform is the result of averaging 100 individual echoes. Over the Salar, these waveforms follow a Gaussian shape. When averaging 100 gaussians, the resulting waveform is a wider gaussian. This effect is named blurring effect. Therefore, when computing the range over this averaged waveform, the result is not as precise as it should be. In order to see the effects of this blurring effect, we have computed the range of each individual echo and we have compared it with the one obtained with Ku and S-band averaged waveforms.

The maximum number of IEs that can be collected over the Salar is 2000 IEs (1 second of data). The initial idea was to use echoes collected over the middle of the Salar. However, it has not been possible and only 500 of them fall into the salar for track 139 and none of them for track 146. So only 500 individual echoes per track are specular and then have been analysed. Figure 8 shows the Orbit-Range (in meters) computed with the 500 Individual Echoes (blue lines), with the Ku-band averaged waveforms (green lines) and with the S-band averaged waveforms (red points) for one of the descendent orbits 139.

For a better comparison, we have averaged the ranges of each group of 100 IEs (blue lines), and we have compared it with the range of the averaged waveforms (green lines) (see Figure 9). And we can see differences of about 1.5 cm.
Figure 9. Ranges from averaged waveform (green) vs. processed in order to have as much IEs as possible.

With these few results we have seen a difference between the range obtained from the IEs and the average waveform range, due to the blurring effect, so the analysis is giving promising and interesting results. It is then worth to continue this study, using more Individual echoes collected over the middle of the Salar.

7. CONCLUSIONS

Ku minus S-band range are more spread than expected when using the GIM ionospheric correction. And still more spread when applying the DORIS iono. This difference between both bands is due to the ionospheric corrections, because RA-2, DORIS and GIM ionospheric corrections present differences of several centimetres. Therefore, if we want to calibrate the S-band, the ionospheric correction should be previously validated.

Moreover, data collected during several years would be useful to study the existence of any seasonal behaviour, and would also help us to clean the data.

Finally, a difference between the ranges computed from the averaged waveforms and the average of ranges obtained with the individual echoes has been observed. This difference goes up to few centimetres at some cases, probably due to the blurring effect. If we want to assess this difference between the Individual echoes and the averaged waveforms, a large amount of data collected over the middle of the Salar should be processed in order to have as much IEs as possible.

8. REFERENCES