Zhang et al.: Use of GNSS SNR data to retrieve soil moisture and vegetation variables over a wheat crop, Hydrol. Earth Syst. Sci. Discuss., doi:10.5194/hess-2017-152, 2017.

RESPONSE TO REVIEWER #2

The authors thank anonymous reviewer 2 for his/her review of the manuscript and for the fruitful comments.

2.1 [General comments
This paper presents a case study applying GNSS signals, which were reflected on the ground surface (soil, vegetation surface) to derive soil moisture and vegetation height data over a wheat crop field. The GPS antenna was installed at a height of 2.51 m. Soil moisture was retrieved as long as the vegetation height was lower than ~20 cm. However, with a further increase in plant height, it was not possible to retrieve soil moisture. Reaching a certain plant height, it was then possible to retrieve the vegetation height from the GNSS signals.
In general, the topic of this manuscript is interesting and worth to be published in HESS. The methods seem valid and transparent. However, before publishing, this manuscript has to undergo major revision as several points have to be clarified and described / discussed better / more clearly. The manuscript should undergo an English spell check. The following points should be improved in general:
- Please highlight in a more prominent way what is really new and what is the outcome and applicability of this approach.]

Response 2.1:

Yes. We will revise the abstract and conclutions to highlight the new results presented in this study.
In particular, the following information will be given:

GNSS SNR data were obtained using the GNSS-IR technique over an intensively cultivated wheat field in southwestern France. The data were used to retrieve either soil moisture or vegetation height during the growing period of wheat. Vegetation growth tended to decrease the relative antenna height and broke up the constant height assumption used in soil moisture retrieval algorithms. Soil moisture could not be retrieved after wheat tillering. A new algorithm based on a wavelet analysis was implemented and used to extract the dominant period of the SNR and further to retrieve vegetation height.

Should a revised version of this paper be accepted in HESS, a copy editing work will be performed.

2.2 [- Please introduce and explain the so called ‘dominant period’ in more detail.]

Response 2.2:

A vegetation height retrieval algorithm is proposed using the dominant SNR period, which is the peak period in the average power spectrum derived from a wavelet analysis of SNR. We will clarify this in the revised manuscript.

2.3 [- Please clarify that the GNSS retrieval of soil moisture and / or vegetation variables, actually only vegetation height, is only valid for different temporal stages. Especially, at the beginning it is unclear / confusing that soil moisture and vegetation height were retrieved at different time periods (before and after vegetation significant growth in March)].

Response 2.3:

Yes. We will replace "vegetation variables" or "vegetation characteristics" by "vegetation height". We will mention in the Abstract that soil moisture and vegetation height were retrieved at different time periods (before and after vegetation significant growth in March).

2.4 [- If the title contains ‘vegetation variables’ but only ‘vegetation height’ is retrieved, please change this in the title and at relevant parts of the manuscript.]

Response 2.4:

Yes. We will modify the title as ‘Use of reflected GNSS SNR data to retrieve either soil moisture or vegetation height over a wheat crop’. We will replace "vegetation variables" or "vegetation characteristics" by "vegetation height" in the entire manuscript.

2.5 [- The structure of the paper is not always clear – especially the chapters ‘Method’, ‘Results’ and ‘Discussion’ should be structured better. Some results / discussions already appear in the methods part, some points of the discussion in the results part and some methods in the discussion part.]

Response 2.5:

Yes. We will revise the manuscript accordingly. In particular, description of Fig. 1 will be moved from Sections 2.1 and 3.2 to Section 4. Description of Fig. 2 will be moved from Sections 3.1 and 3.2 to Section 4. Description of Figs. S3 and S4 will be moved from Section 3.2 to Section 4.

2.6 [- In some parts, the methods are explained very well, but in some parts they are presented too extensively. The manuscript should be more focused on your applied method and should be shortened as many aspects are already published in literature and don’t have to be repeated in this manuscript.]

Response 2.6:

Yes. We will try to improve the focus of Section 3. Note however that all readers of HESS are not familiar with GNSS reflectometry and that Eqs. 1-6 need to be presented.

2.7 [- Is it necessary to retrieve soil moisture before retrieving vegetation height? Please comment on this.]

Response 2.7:

No. It is not necessary to retrieve soil moisture before retrieving vegetation height. This will be made clear in the revised manuscript.

2.8 [- Regarding the statistics, 7 or even only 5 (during the period you used to demonstrate vegetation height) in situ vegetation height samples are actually too low. Please comment at least that during further studies more in situ data should be carried out.]

Response 2.8:

Yes. The in situ vegetation height samples are few, but it must be noted that GNSS height retrievals are totally independent from the in situ measurements. We will make clear that in further studies, more in situ data enabling the characterization of vegetation would be needed.

2.9 [- It is questionable if all information given in the supplement is needed. On the other hand, some figures (see specific comments below) would also be valuable within the manuscript itself and should be presented there.]

Response 2.9:

Yes. We will adjust this in the revised manuscript.

2.10 [Specific comments
Page 1 – Title
Please clarify that the retrieval of soil moisture and vegetation variables are actually only valid for different temporal stages (before and after vegetation significant growth in March). Moreover, it would be valuable to include that you use reflected GNSS signals in your approach as also other GNSS approaches exist on this topic.
Title suggestion: 'Use of reflected GNSS SNR data to retrieve either soil moisture or vegetation height, depending on the vegetation phase of a wheat crop field,']

Response 2.10:

Yes, we will change the title accordingly: 'Use of reflected GNSS SNR data to retrieve either soil moisture or vegetation height over a wheat crop'

2.11 [Page 1 – Abstract

General: The absolute length of the abstract seems fine, however, the information given here should be compressed or information should be combined more functionally. Additionally, it should be added why this approach is generally useful (1 sentence) and what is missing so far regarding the state of art (1 sentence)]

Response 2.11:

Yes. Surface soil moisture can be retrieved based on the linear relationship between in situ soil moisture observations and SNR phases estimated by the Least Square Estimation method, assuming the relative antenna height is constant. However, it is found in this study that the vegetation growth breaks up the constant relative antenna height assumption, and modulates the SNR period. A vegetation height retrieval algorithm is proposed using the SNR dominant period, which is the peak period in the average power spectrum derived from a wavelet analysis of SNR.
We will rephrase the abstract accordingly.

2.12 [p.1, l.15: '...numerical simulations of biomass...']

Response 2.12:

Yes. The sentence will be modified as:

"The retrievals are compared with two independent reference datasets: *in situ* observations of soil moisture and vegetation height, and numerical simulations of soil moisture, vegetation height and above-ground dry biomass from the ISBA (Interactions between Soil, Biosphere and Atmosphere) land surface model."

2.13 [p.1, l. 18: describe in few words the 'dominant period']

Response 2.13:

A vegetation height retrieval algorithm is proposed using the dominant SNR period, which is the peak period in the average power spectrum derived from a wavelet analysis of SNR. We will clarify this in the revised manuscript.

2.14 [p.1, l. 18: '...SNR data, whereas changes in...']

Response 2.14:

Yes. The sentence will be rephrased accordingly.

2.15 [p.1, l. 20: '...smaller than one wavelength (~19 cm).' This should also be changed in the entire manuscript.]

Response 2.15:

Yes. We will correct it.

"Surface volumetric soil moisture can be estimated (R^2 = 0.73, RMSE = 0.014 m^3m^{-3}) when the wheat is smaller than one wavelength (~ 19 cm)."

2.16 [p.1, l. 22: dry biomass?]

Response 2.16:

Yes. We will correct this.

2.17 [Page 1-3: 1. Introduction
General: The introduction is quite good, but it should be written more comprehensively, especially the parts where you describe already published techniques. However, the first part (p.1, l.27-p.2, l.2) where you introduce the necessity of this approach and the recent lack to monitor land surface variables at a local scale should be extended! Moreover, it should be written more clearly why GNSS reflectometry could be a solution.]

Response 2.17:

In situ VSM observations are not widespread in France and in situ vegetation height observations are generally not available. Therefore, ISBA (Interactions between Soil, Biosphere and Atmosphere) simulations are key for water resource monitoring at the country scale. It must be noted that the ISBA model is forced by the SAFRAN atmospheric analysis and that SAFRAN is able to integrate thousands of in situ raingage observations. ISBA is also able to simulate vegetation characteristics such as vegetation height, leaf area index, and above-ground dry biomass. However, in situ VSM observations are needed to validate land surface models and/or satellite-derived products (e.g. Albergel et al., 2010). From this point of view, the spatial resolution of GNSS retrievals is an asset. The area sampled by GNSS retrievals is much larger than what can be achieved using individual soil moisture probes and much smaller than pixel size of satellite-derived products. Longer time periods of GNSS retrievals should be envisaged to serve as independent validation data sources in statistical methods such as Triple Collocation (Dorigo et al., 2010).
We will incorporate this material in the revised manuscript.

References:

Albergel, C., J.-C. Calvet, P. de Rosnay, G. Balsamo, W. Wagner, S. Hasenauer, V. Naemi, E. Martin, E. Bazile, F. Bouyssel, J.-F. Mahfouf, “Cross-evaluation of modelled and remotely sensed surface soil moisture with in situ data in southwestern France”, Hydrol. Earth Syst. Sci., 14, 2177–2191, 2010b.

Dorigo, W. A., Scipal, K., Parinussa, R. M., Liu, Y. Y., Wagner, W., de Jeu, R. A. M., and Naeimi, V.: Error characterisation of global active and passive microwave soil moisture datasets, Hydrol. Earth Syst. Sci., 14, 2605–2616, doi:10.5194/hess-14-2605-2010, 2010.

2.18 [p.2, l.7: The frequency of GPS L1-band is 1.57542 GHz. Please write 1.6 GHz instead of 1.5 GHz.]

Response 2.18:

Yes. We will correct it.

"GNSS satellites operate at the L-band microwave frequency domain (between 1.2 GHz and 1.6 GHz). "

2.19 [p.2, l.10: ‘These properties have e.g. been...’]

Response 2.19:

Yes. We will correct it.

2.20 [p.2, l.10-15: As you generally mention L-band active and passive remote sensing techniques, also other GNSS methods (besides reflectometry) aiming to derive soil moisture or vegetation parameters should be mentioned (e.g. GNSS methods using signal attenuation).]

Response 2.20:

Yes. We will cite a reference using GNSS signal strength attenuation.
Larson et al. (2008) showed that SNR data obtained from existing networks with single ground-based geodetic GNSS-IR antenna can be used to infer soil moisture. Other GNSS methods (besides reflectometry) can be used. For example, Koch et al. (2016) used three geodetic GNSS antennas (one was installed above the soil, the other two were buried at a depth of 10 cm), to measure the GNSS signal strength attenuation and to retrieve soil moisture over bare soil.

<u>References</u>:

Koch, F., Schlenz, F., Prasch, M., Appel, F., Ruf, T. and Mauser, W.: Soil moisture retrieval based on GPS signal strength attenuation, Water, 8(7), 276, 2016.

2.21 [p.2, l.17: please specify, how these two antennas are mounted?]

Response 2.21:

Yes. We will clarify it in the revised manuscript.

"(1) waveform acquisition with a specific receiver using two antennas (one zenith-oriented antenna and one surface-oriented antenna), called GNSS reflectometry (GNSS-R) (Zavarotny et al., 2014) or (2) GNSS signal strength, Signal-to-Noise Ratio (SNR), acquisition with classical geodetic receiver using one antenna, called GNSS interferometric reflectometry (GNSS-IR) technique (Larson, 2016). "

2.22 [p.2, l.26: ‘They are surrounded by sparse vegetation and are therefore not useful for vegetation studies.’]

Response 2.22:

Yes. The sentence will be modified accordingly.

2.23 [p.3, l.31/32: Better write ‘lower and taller vegetation’ as you are measuring the vegetation height and not their density.]

Response 2.23:

Yes. This sentence will be rephrased accordingly.

2.24 [Page 4-5: 2. Data
General: Actually this section already belongs to the ‘Method’ section.
p.4, l.4: Fig. S1: This figure is not really valuable to show where the test field is situated (present either a picture of the GNSS antenna in the field or a map where the field is situated)]

Response 2.24:

Yes. We will reorganize Sections 2 and 3 in a single "Materials and methods" Section.
We will present a picture of the GNSS antenna in the field (see Fig. R2.1).

Figure R2.1 - Antenna of the GNSS site at 2.51 m above the soil surface over an experimental field covered by rainfed winter wheat in Lamasquère, France (43°29'10"N, 1°13'57"E).

2.25 [p.4, l.14: '..., four GPS satellites of in total 32...]

Response 2.25:

Yes. The sentence will be modified.
For our site, four GPS satellites out of 32 were excluded from the analysis because their data were incomplete.

2.26 [p.4, l.18: refer to relevant figure]

Response 2.26:

Yes. We will refer to Figure 1a here. Figure 1a shows an example of the multipath SNR data after detrending for the ascending track of GPS01 on 21 January 2015. The periodic signature of the multipath SNR data is visible.

2.27 [p.4, l.1-2 and l.29: avoid repetitions]

Response 2.27:

Yes. The repeated sentence (P.4, L.29) will be deleted.

2.28 [p.4, l.1ff: add information on the soil type and texture; moreover, the row spacing of the wheat crop would be interesting.]

Response 2.28:

Yes. We will add relevant the available information on soil and crop properties.
Soil in the close vicinity of the antenna consisted of 18% of sand, 41% of clay, and 41% of silt. The row spacing of the wheat crop was 15 cm.

2.29 [p.4, l.30/31: which satellite observations are meant? GNSS satellites or EO satellites?]

Response 2.29:

EO satellites. The sentence will be modified.

2.30 [p.5, l.2: 'soil moisture and vegetation height...']

Response 2.30:

Yes. The sentence will be corrected ("height" will be added).

2.31 [p.5, l.5: Which soil moisture instruments did you use as reference, e.g. frequency domain probes?]

Response 2.31:

Yes, FDR ML3 Thetaprobes were used. We will clarify it in the revised manuscript.

2.32 [p.5, l.8: add the vegetation height at the end of the season as well. Moreover, for each reference sample the measured height and the phenological status of the wheat crop would be interesting (e.g. listed in a table).]

Response 2.32:

Yes. We will add information on the vegetation height and phenological status in the revised manuscript.
The canopy height was about 0.39 m on 18 June because of a lodging event.

2.33 [p.20, Fig. 1: Figure sub-captions (a-d) are not well structured; a legend in plot a) would be helpful (red and black line); please insert units if there are in y-axis of plot b) and plot d) and in the legend of plot c) (otherwise write []); the mentioned 128 to 1024 s are not shown in plot c –please mark or show tem additionally in a second x-axis; for more clarity in the manuscript, refer to Fig. 1a, 1b, 1c, 1d, not only to Fig. 1.]

Response 2.33:

Yes. We will modify this figure. The units are $V^2V^{-2}s^{-1}$ for the y-axis of plot (b) and plot (d) and the legend of plot (c). y-axis of plot (c) ranges from 128 to 1024 s. We will clarify Figure 1.

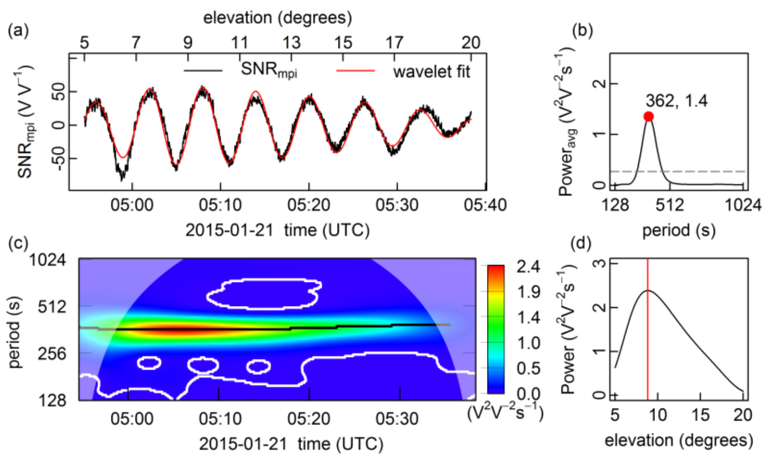

Figure R2.2 - Example of a usable GPS01 ascending track SNR data set from 04:50 UTC to 05:38 UTC on 21 January 2015: (a) Multipath SNR data (in V V^{-1}), (b) average power spectrum and (c) power spectrum for periods from 128 to 1024 s. The red line in (a) is the reconstructed SNR data by the daughter wavelet corresponding to the peak period (362 s) indicated in (b). The power at the peak period across elevation angles (d) presents a maximum value at an elevation angle of about 9 degrees.

2.34 [Page 5-9: Methods
General: This chapter should be written more comprehensively and precisely, especially the parts of already known methods.
p.6, l.8ff: How many soil moisture and vegetation height results per day did you get out of the 37 available satellite tracks? As of Table 1 and Table 3 it seems that you got 1 results for each day. Please clarify (short) already at this point the temporal resolution and the daily composition of your retrieved results.]

Response 2.34:

Yes, there is one result for each day. The median soil moisture estimate from all available satellite tracks (66 per day) that passed at different times during the day was used as the final soil moisture estimate. The final retrieved vegetation height (*H*) was based on the mean height change from all available satellite tracks (37 per day), plus one wavelength.

2.35 [p.7, l.3: Is there any S-value specific for L1 already available in literature? Or is the mentioned and an adjusted S-value for the first time applied for L1-band signals? Then this should be introduced more prominently in the manuscript!]

Response 2.35:

In PBO H_2O network, only L2C is considered to retrieve soil moisture. There is no specific S parameter for L1. We adjusted S parameter to provide better results. Because the slope between in situ observations and SNR phase in our case is obviously different from the a priori S value, although the correlation is high. Moreover, it can be proposed to use a scaled wetness index to retrieve a scaled value of VSM. In this case, using the S parameter is not needed. For many applications, a scaled value of VSM is sufficient.
Additionally, Vey et al. (2015) used the method and S parameter value from Chew et al. with L1, L2P and L2C SNR data over a long period of time (2008-2014) for a site presenting a high percentage of bare soil. They compared VSM estimates from L1 data with VSM estimates from L2C data. They obtained the following VSM scores: RMSD was 0.03 m^3m^{-3}, and the regression slope was 1.03.

2.36 [p.7, l.5: It seems more logical to introduce the adjusted S-value in this chapter instead in the ‘Results’ chapter.]

Response 2.36:

Yes. We will adjust this in the revised manuscript, moving the sentences in the 'Results' Section:
"This adjusted slope value (S = 0.0033 $m^3m^{-3}degree^{-1}$) is the mean of slope values obtained for satellite tracks whose phase presents a linear correlation with *in situ* soil moisture higher than 0.9. This occurred for the ascending tracks of GPS 13, 21, 24, 30 and for the descending tracks of GPS 05, 09, 10, 15, and 23."

2.37 [p.7, l.6ff: Perhaps it also makes sense to introduce your experimental A_norm threshold of 0.88 within this chapter. Moreover, Fig 2 should be combined with / replaced by Fig. S7.]

Response 2.37:

Yes. Fig. 2 will be replaced by Fig. S7 in the revised manuscript; and Fig. S7 will be removed from the supplement. We will also introduce A_{norm} threshold of 0.88 here.

2.38 [p.7,12/13: are GNSS data available for periods of bare soil (e.g. before the wheat crops reached a vegetation height of 10 cm before January 16th) – this would be valuable to improve the final soil moisture estimate.]

Response 2.38:

We don't have GNSS data for periods of bare soil. The available data started being collected on 6 December 2014, and wheat had started growing (in situ height measurement was 10 cm on 17 December 2014). Because of discontinuities in the availability of both *in situ* soil moisture data and GNSS data before 16 January 2015, we started our analysis on 16 January 2015. Longer periods of time including bare soil situations should be investigated in further studies. (See Response 2.53)

2.39 [p.7, l.21: 'see the Supplement' – which figure or part do you mean?]

Response 2.39:

We mean Eqs. S1-S4 in the Supplement. We will clarify it in the revised manuscript.

2.40 [p. 8, l.9ff: 'One possible reason...' This part fits better to the 'Discussion' part.]

Response 2.40:

Yes. We will move this part to the Discussion section.

2.41 [p.9, l.8ff: In my opinion, the 'scores' don't have to be introduced with equations.]

Response 2.41:

We will move Section 3.3 to the Supplement.

2.42 [p.21, Fig. 2: Should/could be combined with Fig. S7. Figure S3 and S4: Especially Fig. S4 is interesting. It should be demonstrated within the manuscript as it shows at which stages it is difficult to retrieve the results according to the dominant period.]

Response 2.42:

Yes. Fig. 2 will be replaced by Fig. S7. And we will move Fig. S4 from the supplement to the manuscript.
After 10 March, wheat height exceeded one wavelength (> 0.19 m). In addition to lower A_{norm} values, an increasing number of unsuitable tracks was observed till 20 March, together with low values of peak power. The vegetation gradually decreased the strength of the signal reflected from the soil surface but increased the signal reflected from vegetation, causing more than one peak. The quality of such track data was considered too poor for retrieving biophysical variables. When the vegetation surface completely replaced the soil surface as the dominant reflecting surface of the GNSS signal, a single peak period was observed again and its value increased in response to the rise of the reflecting vegetation surface. We will revise the manuscript accordingly.

2.43 [Page 10-11: Results
p.10, l.3ff: Please insert also the mean soil moisture values of each method (for the entire observation period).]

Response 2.43:

Yes. The mean soil moisture values during the experimental period are 0.274 m^3m^{-3} for *in situ* VSM measurements, 0.281 m^3m^{-3} for ISBA simulations, 0.305 m^3m^{-3} for GPS retrievals with S=0.0148 $m^3m^{-3}degree^{-1}$, 0.264 m^3m^{-3} for GPS retrievals with S=0.0033 $m^3m^{-3}degree^{-1}$, and 0.276 m^3m^{-3} for GPS retrievals from the scaled soil wetness index.

2.44 [p.10, l. 3-24 and p.23, Fig. 4: Is it generally possible to compare these three methods one by one? The model simulates the first 10 cm; the reference measurements record at a soil depth of 5 cm and the GPS technique observes the soil surface. Perhaps the results with a S-value of S=0.0148 are even more realistic!? Please state on this. The GPS retrieval seems to be slightly too low in this plot using a S-value of 0.0033; especially after soil freezing and at the end of the soil moisture retrieval period the correlation between GPS retrievals and observations / reference measurements is weaker.]

Response 2.44:

Yes. Chew et al. (2014) used an electrodynamic single-scattering forward model to test the empirical relationships observed in field data, showing that SNR phase is affected by soil moisture in the top 5 cm of the soil. Moreover, surface soil moisture (< 1 cm depth) exerts the strongest control. Validation VSM obervations over the top 6 cm were used in Small et al. (2016), using the same a priori S parameter value.
We checked that the top 1 cm VSM simulations by ISBA are very close to the simulations of the top 10 cm VSM. In order to keep the method as generic as possible, we didn't directly adjust the slope from the median phase value from all available satellites. This adjusted slope value is the mean of slope values obtained for satellite tracks whose phase presents a linear correlation with *in situ* soil moisture higher than 0.9. This is why VSM retrievals are slightly too low in Fig. 4. The scores confirmed the VSM retrievals with the adjusted S parameter are closer to the in situ observations at 5 cm. Furthermore, a scaled soil wetness index can be considered, instead of VSM in m^3m^{-3} (see response 2.35).

The detail method is described below:
The phase time series can be normalized for each satellite track. Then the median value of the normalized phases from all available satellite tracks can be considered as the final soil wetness index (φ_{index}) for each day as shown in Fig. R2.3 (red line):

$$\varphi_{index} = \frac{\varphi - \varphi_{\min}}{\varphi_{\max} - \varphi_{\min}} \tag{R2.1}$$

This soil wetness index time series is linearly related with in situ observations ($R^2 = 0.74$) and ISBA simulations ($R^2 = 0.65$). Moreover, VSM can be estimated from φ_{index}

$$VSM = VSM_{obs\_\min} + \varphi_{index} \cdot (VSM_{obs\_\max} - VSM_{obs\_\min}) \tag{R2.2}$$

VSM_{obs_min} and VSM_{obs_max} are the minimum and maximum *in situ* VSM observations during the experimental time period, respectively. Figure R2.4 presents the estimated VSM from GPS soil wetness index (φ_{index}), together with *in situ* VSM observations and ISBA simulations. More related scores are shown in Table R2.1 and the scatter plot between GPS retrievals from φ_{index} and *in situ* observations are shown in Fig. R2.5. We will present these results in the revised manuscript.

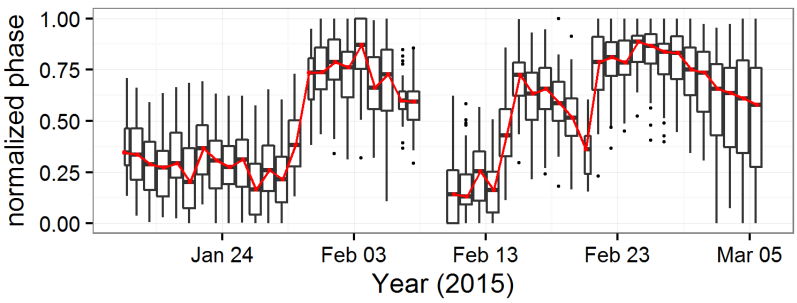

Figure R2.3 - Median of the daily GPS normalized phases (soil wetness index, red line) and their daily statistical distribution (black box plots) for all available satellite tracks from 16 January to 5 March 2015.

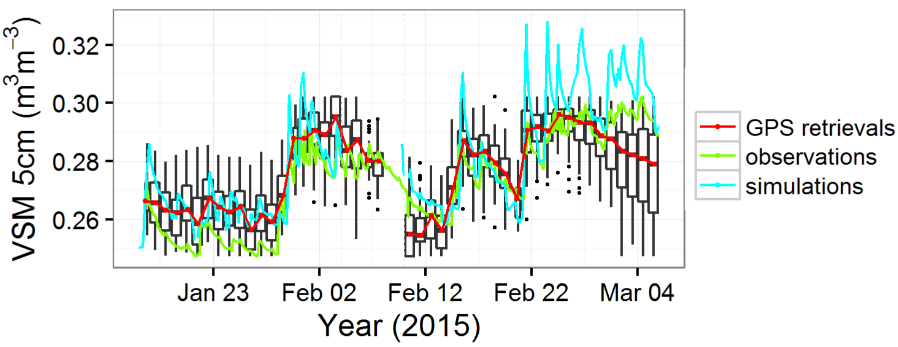

Figure R2.4 - In situ daily mean surface volumetric soil moisture (VSM) observations at 5 cm depth (green line), ISBA daily mean simulations (blue line), median of the daily GPS retrievals with soil wetness index (red line) and their daily statistical distribution (black box plots) for all available satellite tracks from 16 January to 5 March 2015.

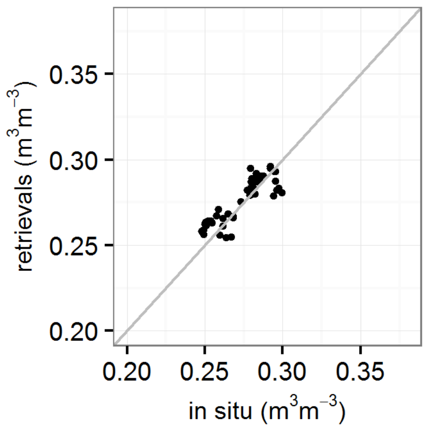

Figure R2.5 - Scatterplot between GPS retrievals (Eq. (R2.1)) and *in situ* VSM observations (m^3m^{-3}) from 16 January to 5 March 2015.

Table R2.1. Soil moisture scores from 16 January to 5 March 2015.

	GPS vs. *in situ*	GPS vs. ISBA	GPS vs. *in situ*	GPS vs. ISBA	GPS (φ_{index}) vs. *in situ*	GPS (φ_{index}) vs. ISBA	ISBA vs. *in situ*
S ($m^3m^{-3}deg^{-1}$)	0.0148		0.0033		-	-	-
N	47	43	47	43	47	43	43
MAE (m^3m^{-3})	0.036	0.034	0.011	0.018	0.007	0.009	0.009
RMSE (m^3m^{-3})	0.046	0.041	0.014	0.022	0.009	0.012	0.010
SDD (m^3m^{-3})	0.036	0.037	0.009	0.012	0.008	0.011	0.006
Mean bias (m^3m^{-3})	0.029	0.019	-0.010	-0.018	0.003	-0.005	0.008
R^2	0.73	0.63	0.73	0.63	0.74	0.65	0.88

2.45 [p.10, l. 14: ‘a priori’

Response 2.45:

Yes. We will correct it.

2.46 [p.11, l.6: delete ‘(not shown)’]

Response 2.46:

OK.

2.47 [p.11, l.10ff: Please insert also the vegetation height determined either by GNSS or manually for each date, instead only listing the deviations.]

Response 2.47:

Yes. We will add a table to include this information in the revised manuscript.

Table R2.2 - Vegetation height retrievals from GPS and simulations from ISBA, and their relative deviations for each in situ height observation.

Dates (Year 2015)	*in situ* height (cm)	GPS height (cm)	ISBA height (cm)	*in situ* - GPS (cm)	*in situ* - ISBA (cm)
20 January	10	18.4	15.4	-8.4	-5.4
10 March	20	15.7	14.5	4.3	5.5
30 March	35	40.4	24.6	-5.4	10.4
24 April	55	65.3	70.0	-10.3	-15.0
19 May	97	102.9	100.0	-5.9	-3.0
29 May	100	101.7	100.0	-1.7	0.0
18 June	39	40.5	100.0	-1.5	-61.0

2.48 [p.11, l.12: why do you use a 21 gliding window approach? Is this really necessary? Perhaps the vegetation height levels in Figure 6 make sense (e.g. due to meteorological events and plant growth spurts)?]

Response 2.48:

The possible causes of the leveling effect are discussed in Section 5: (1) the occurrence of more than one dominant reflecting surface at different heights (Sect. 5.3) and (2) rapid phenological changes in the wheat canopy triggering a response of the H retrieval (Sect. 5.5). It must be noted that absolute daily changes in H (and h), of about 1.1 cm d^{-1} are fairly uniform throughout the growing period. Since h decreases when plants grow, relative changes in h tend to increase. According to Eq. 4, T behaves similarly. This means that the sensitivity of the retrieval method to changes in H is larger at the end of the growing period. This is probably why leveling is more pronounced between mid-March and mid-April than at the end of April (see Fig. 7). Leveling is less noticeable in May. A moving average permits smoothing the height retrievals, and presenting a better fit to the in situ observations.

2.49 [p.11, l.26: Please state more on the overall possibility to compare dry biomass and vegetation height. Is this really possible? Are there some references available? Please state on this more detailed.]

Response 2.49:

We found a linear relationship between the moving average height from GPS retrievals and the above-ground dry biomass simulated by the ISBA model from 10 March to 29 May 2015 (when the maximum vegetation height, 1 m, was measured), during the time period from tillering to flowering. The correlation coefficient between the moving height and the dry biomass, with 81 observations, was 0.996.

$$dry\_mass = 1.05 \times moving\_height - 0.19 \quad \text{(R2.3)}$$

with with dry mass in kg m^{-2} and moving_height in meter.

A similar result was obtained by Wigneron et al. (2002) over another wheat crop site (Triticum durum, cultivar prinqual) in spring 1993. Although the sowing date (19 March) was late and the crop cycle was rather short, there was still a very good linear relationship between the in situ wheat height measurements and in situ dry biomass measurements from 20 April to 11 June 1993 (when the maximum vegetation height, 1 m, was measured). The correlation coefficient with 25 observations is 0.996.

$$dry\_mass = 1.11 \times height - 0.19 \quad \text{(R2.4)}$$

with dry mass in kg m^{-2} and height in meter.

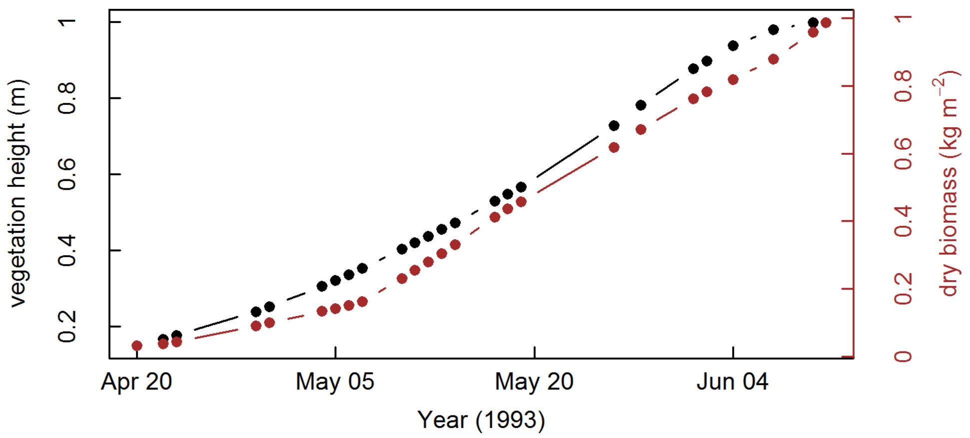

Figure R2.6 - In situ wheat canopy height measurements (25 black dots) and in situ wheat dry biomass measurements (brown dots) from 20 April to 11 June 1993 (adapted from Wigneron et al., 2002).

<u>Reference</u>:

Wigneron, J.P., Chanzy, A., Calvet, J.C., Olioso, A. and Kerr, Y.: Modeling approaches to assimilating L band passive microwave observations over land surfaces. Journal of Geophysical Research: Atmospheres, 107(D14), 2002.

2.50 [p.22/23, Fig. 3/4: for better comparability, in both Figures the y-axis should have the same scale; They could also be combined in one figure with sub-figures a] and b].]

Response 2.50:

Yes. We will modify the figures, and combine them in one figure. We will also add the retrievals from scaled soil wetness index. On the other hand, using the same y-axis scale for all sub-figures is not possible, as some sub-figures become unreadable.

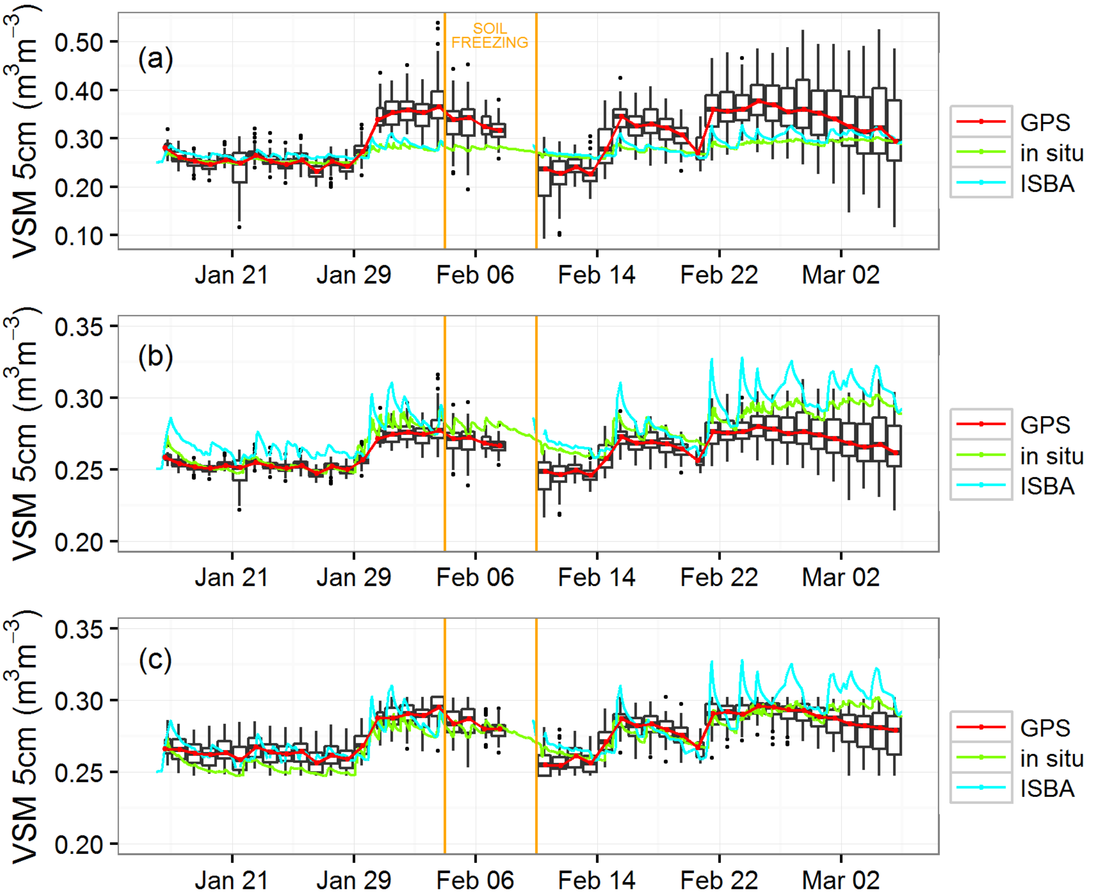

Figure R2.7 - *In situ* daily mean surface volumetric soil moisture (VSM) observations at 5 cm depth (green line), ISBA daily mean simulations (blue line), median of the daily GPS retrievals (a) with a priori slope (S = 0.0148 $m^3m^{-3}deg^{-1}$) (red line), (b) with a local fitted slope (S = 0.0033 $m^3m^{-3}deg^{-1}$) (red line) and (c) from scaled soil wetness index (red line), and their daily statistical distribution (black box plots) for all available satellite tracks from 16 January to 5 March 2015. Boxes: 25-75% percentiles; bars: maximum (minimum) values below (above) 1.5 IQR (Inter Quartile Range, corresponding to the 25-75% percentile interval); dots: data outside the 1.5 IQR interval. The ISBA simulations indicate soil freezing (i.e. the presence of ice in the top soil layer) from 4 to 9 February (between the orange lines).

2.51 [p.24, Fig. 5: How many dots are shown in this plot (N=47?)? Please add this information in the figure capture.]

Response 2.51:

Yes, there are 47 dots in Fig. 5. We will clarify that.

2.52 [p.25, Fig 6: You don't have to repeat the legend in the figure column.]

Response 2.52:
OK.

2.53 [Page 12-14: Discussion
General: The idea of asking questions is good. Please also insert a discussion section / further question on the potential future applicability and transferability (e.g. to other soils, other vegetation types, other GNSS signals etc.). What could be improved...]

Response 2.53:

Yes, we could add another discussion subsection about the potential future applicability and transferability of the retrieval method.

We successfully assessed the surface soil moisture retrieval technique over a wheat crop field, during the start of the growing period. However, the rather narrow range of surface soil moisture values during the corresponding experiment time period limited the representativeness of the obtained retrieval accuracy. Furthermore, our dataset did not include GNSS data and in situ VSM measurements for periods of bare soil. Longer periods presenting a bare soil surface should be investigated in further studies. At the same time, more in situ vegetation measurements should be carried out for further studies.
The retrieved vegetation height was based on the dominant period of the average power spectrum. The latter was derived from GPS multipath SNR data for elevation angles between 5 and 20 degrees. We only considered the dominant period variations, without accounting for instantaneous phase changes. The accuracy of the retrieved vegetation height could probably be improved considering changes in both period and phase of the multipath SNR oscillations.
In this study, only the SNR data of L1 C/A signal is used, SNR data from different wavelength (e.g., L1 C/A, L2C and L5) should also be compared or combined to survey canopy characteristics.
A linear relationship between wheat height and above-ground dry biomass was observed during the period from wheat tillering to ripening. Retrieving dry biomass is a motivation for further research because most current satellite vegetation products focus on retrieving vegetation indexes or leaf area index. The dry biomass is directly related to the wheat yield, and retrieving wheat height could have applications in crop monitoring.
In this study, only wheat is considered. Other crops should be investigated in the future. Additionally, the algorithm we proposed might also be suitable to retrieve snow depth.

We will add this in the revised manuscript.

2.54 [p.12, l.3ff: As important findings (regarding the discussion) are shown in Fig. S6, this figure should also be shown in the manuscript (not only the supplement). Moreover, this issue should be discussed in more detail.]

Response 2.54:

Yes. We will add Fig. S6 to the revised manuscript and adjust its legend.

We tested the relationship between the multipath phase (φ_{mpi}) in Eq. (5) and soil moisture for the whole wheat growing cycle. We found that when the vegetation effects are not significant ($A_{norm} > 0.78$), φ_{mpi} correlates well (R = 0.92) with the *in situ* soil moisture observations (N = 47, Fig. R2.8a). During this time period, the variation of φ_{mpi} is only about 12 degrees in relation to the change of the in situ VSM between 0.25 m^3m^{-3} and 0.30 m^3m^{-3}. But when the vegetation effects are significant ($A_{norm} < 0.78$), φ_{mpi} (without or with unwrapping, Fig. R2.8b and R2.8c) is no longer linear related to soil moisture. For example, when vegetation height exceeded one wavelength, φ_{mpi} rapidly decreased from 207 degrees to 43 degrees (between 10 and 20 March). Changes in φ_{mpi} are disconnected from ISBA simulations. This is consistent with CH15, who showed that under this situation soil moisture cannot be retrieved unless vegetation effects are corrected for.

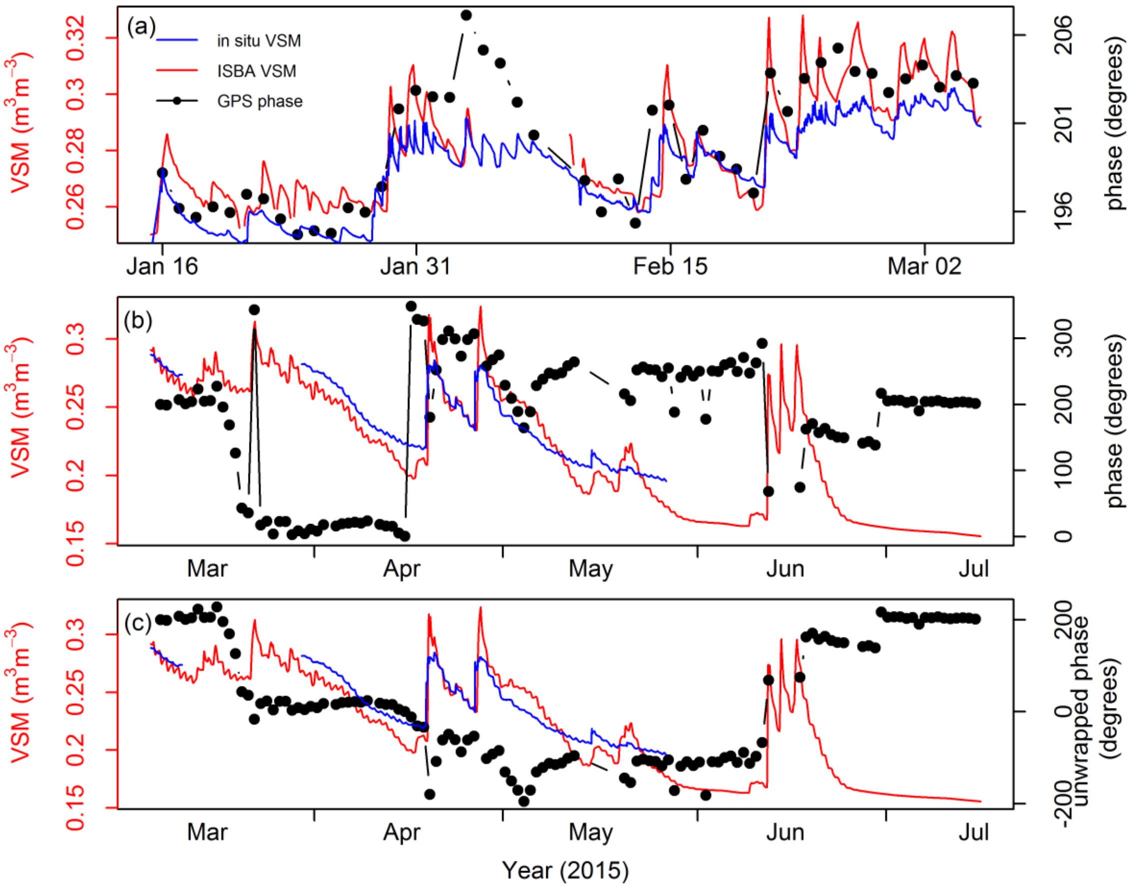

Figure R2.8 - Example of a track data set (descending tracks from GPS10): (a) from 16 January to 5 March, with no significant vegetation effects; (b) and (c) from 6 March to 15 July, with significant vegetation effects. In (a) and (b), multipath phases (black dots) are compared with *in situ* VSM measurements at 5 cm (blue line) and ISBA simulations (red line). In (c), unwrapped multipath phases (black dots) are used to compare with *in situ* and simulated VSM.

2.55 [p.12, l.9: Why did you increase this threshold exactly to the value 0.88? Is there any reason for this value?]

Response 2.55:

Adjusting the A_{norm} threshold from 0.78 to 0.88 permits making a distinction between harvest and post-harvest (after 30 June) A_{norm} values in Fig. S7.

2.56 [p.12, l.26: Re-formulate your question: ‘Can other vegetation characteristic besides vegetation height be inferred from the wavelet analysis?’. Or formulate two questions: ‘Can vegetation height be inferred from...?’ and ‘Is it possible to additionally retrieve other vegetation characteristics from...?’]

Response 2.56:

Yes. We will modify it as 'Can vegetation water content be inferred from the wavelet analysis?'

2.57 [p.12, l.27ff: The idea that you potentially also would like to retrieve the plant water content (or even other vegetation characteristics) should already be introduced earlier in the manuscript. Then an answer to this question would make more sense in the ‘Discussion’ part. Do you have reference data that show a decrease in plant water content?]

Response 2.57:
The VWC variable is already mentioned in the Introduction (P. 3, L. 19). The idea of retrieving VWC will be expressed more clearly.
The conclusions of this paragraph are based on destructive gravimetric measurements (not shown).

2.58 [p.13, l.22: What do you mean with STD?]

Response 2.58:

Yes, we mean "daily standard deviation score". We will clarify it.

2.59 [p.13, l.17: The rainfall/meteorological and logging events could additionally be shown in the figure, e.g., as a subplot.]

Response 2.59:

The exact day when the lodging event happened is unknown, we can only infer it happened between 29 May and 18 June. The height measurements on 29 May and 18 June are 100 cm and 39 cm, respectively. We will add Fig. S9 into Fig. 7 for better comparing with rainfall data. However, whether maximum STD is an indicator of lodging or not is unclear.

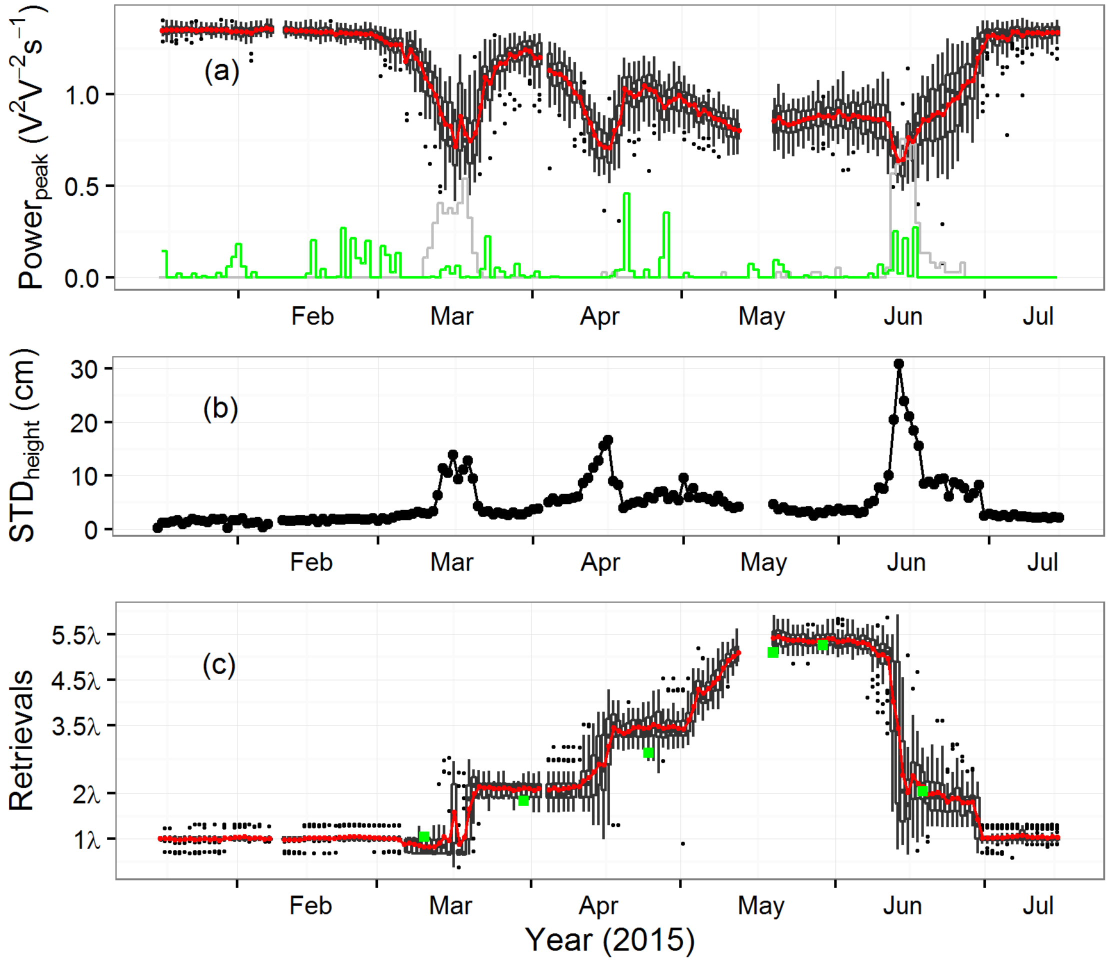

Figure R2.9 - The box plots of (a) the peak power from a wavelet analysis, (b) standard deviation (STD) score of the retrieved vegetation height and (c) the retrieved vegetation height (rescaled in λ units) for all available satellite tracks from 16 January to 15 July 2015. The mean value of the peak power in (a) and of the retrievals in (c) are shown by red lines. In (a), the grey line shows the statistical distribution of bad quality tracks (the number of the bad quality tracks can be obtained multiplying by 37), the green line represents the rainfall (daily precipitation in mm d^{-1} can be obtained multiplying by 50). In (b), the rescaled *in situ* observations are shown by green squares.

2.60 [p.14, l.2-8: This actually belongs to the 'Method' chapter. It is a further method to compare your retrievals to a reference.]

Response 2.60:

Yes. We will introduce the GDD model in the 'Method' chapter.

2.61 [Page 14-15: Conclusions
General: Give also an outlook on potential applicability of this technique.]

Response 2.61:

We will add a summary of the new Discussion section (See Response 2.53)

2.62 [p.14, l.19: Please specify – is this a new algorithm you developed or do you mean at this point the algorithm of CH15 and others you applied for the wheat crop test field?]

Response 2.62:

A new algorithm based on a wavelet analysis was implemented for retrieving vegetation height. We will clarify it in the revised manuscript.

2.63 [p.15, l.2: L5 is introduced here for the first time. It could be mentioned already earlier (e.g., in the 'Discussion').]

Response 2.63:

Yes. We will refer to L5 in the Discussion. (See Response 2.53)

2.64 [Supplement
S p.1, Fig. S1: see comment above.]

Response 2.64:

Yes. We will present a picture of the GNSS antenna in the field. (See Response 2.24)

2.65 [S p.2, Fig. S2: Applying the same time scale in the x-axis of the two plots would be better for comparability or it would even be more helpful if both plots would be combined in one figure (e.g. with two different colours).]

Response 2.65:

Yes. We will use the same time scale in the x-axis of the two plots.

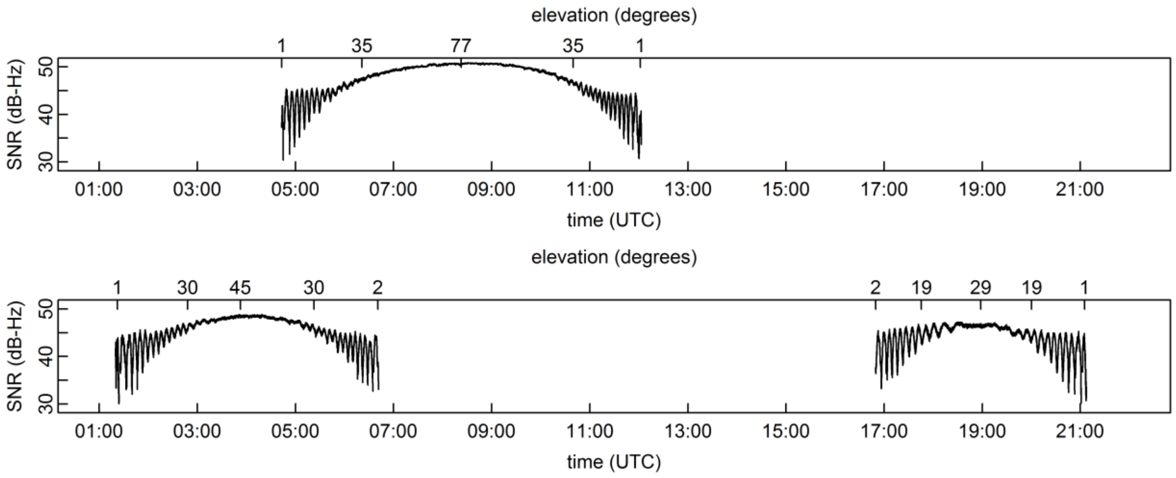

Figure R2.10 - Recorded S1C SNR data at Lamasquère for (top) GPS01 and (bottom) GPS18, on 21 January 2015.

2.66 [S p.4, Fig. S3: a legend would be useful; it would be logical for comparison to combine Fig. S3 and Fig. S8]

Response 2.66:

Yes. We will add a legend and combine Fig. S3 and Fig. S8.

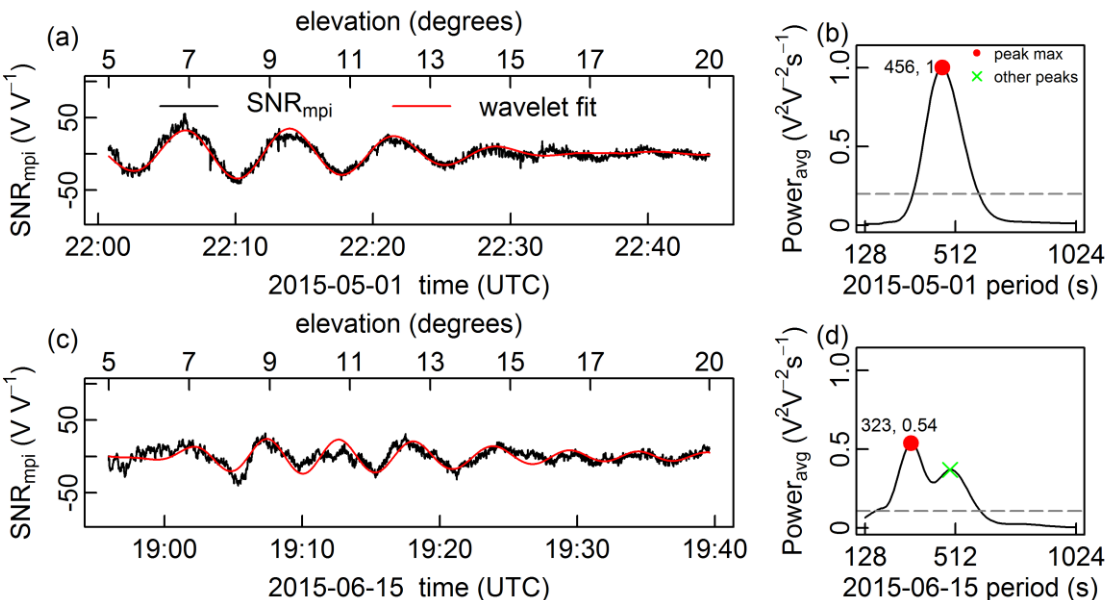

Figure R2.11 - Examples of (a) usable and (c) unusable track data sets from the ascending tracks of GPS01 on 1 May 2015 and 15 June 2015, respectively: (a, c) multipath SNR data, and (b, d) average power spectrums. The red lines in (a, c) are the reconstructed SNR data by the daughter wavelet corresponding to the maximum peak periods in (b, d), respectively. The green crosses in (d) shows there is more than one peak in the track data, indicating poor quality, unusable data.

2.67 [S p.5, Fig. S4: see comment above; insert a legend and units if needed.]

Response 2.67:

Yes. We will add units in this figure and move it to the manuscript.

2.68 [S p.6, Fig. S5: see comment above; how many dots are shown in this plot (N=47?)? Please add this information in the figure capture.]

Response 2.68:

Yes, N=47, we will clarify it in the figure capture.

2.69 [S p.7, Fig. S6: please add the black dots also to the legend; regarding the blue line / dots: use either dots or lines for all of the three plots.]

Response 2.69:

Yes. We will modify this figure. (See Response 2.54).

2.70 [S p.8, Fig. S7: see comment above.]

Response 2.70:

Yes. Figure S7 will replace Fig. 2 in the manuscript.

2.71 [S p.9, Fig. S8: see comment above.]

Response 2.71:
Yes. We will modify this figure. (See Response 2.66)

2.72 [S p.9, Fig. S9: This information could visually be combined with Fig. 2 / Fig S8.]

Response 2.72:
We will add Fig. S9 into Fig. 7 for better comparing with rainfall data.

2.73 [S p. 11: Duveiller et al. 2011 should also be added to the references in the manuscript.]

Response 2.73:

OK.

2.74 [S p. 12: Please clarify the figure capture. Was is actually meant with '...the value retrieved 15 days before, ...'? The dates of flowering and ripening should also occur in the figure or at least in the figure capture.]

Response 2.74:

Yes. We will clarify the caption of Fig. S12.
Figure S12 shows the diffrence between retrieved vegetation height at a given date and retrieved vegetation height 15 days before, from 31 January to 11 June 2015.