Interactive comment on "Combined use of optical and radar satellite data for the monitoring of irrigation and soil moisture of wheat crops" by R. Fieuzal et al.

Answers to the anonymous Referee #1

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Our answers are given after each question or remark of the reviewer, the latter being in bold type.

This paper addresses the possibility of using combined optical visible/near-infrared and radar C-band data for monitoring the phenological development of wheat crops, and in particular soil moisture evolution with the ultimate potential objective of optimization of irrigation practices.

The selected area is especially adequate for testing such methodologies, due to the adequate surface conditions, homogeneity, lack of topographic disturbances, adequate climatic conditions, convenient for acquisition of time series of optical data, and availability of field measurements as required for validation purposes.

However, the case is rather unique, because the methodology is based on the availability of a large time series of high resolution optical data (FORMOSAT in this case) which are not easily available in most places. ENVISAR/ASAR is used in this case to provide the time series of radar data.

One first question is about the criticality of having such as dense time series of optical data, and how critical is to have such series on such high spatial resolution. Since the radar data have 30 m spatial resolution, and the accuracy in geolocation is of about 50 m (as reported in the paper) one could use other optical data, even Landsat TM or other similar data, which are much more easily available, at such spatial resolution of 30-50 m. In fact, all what is used from the optical data is just NDVI, for which only two spectral bands are required, and those bands are available is almost every satellite. In this way the method becomes less dependent on the particular availability of FORMOSAT time series of data for this purpose.

This remark is very relevant. However, one of the positive perspectives in optical Earth remote sensing is that dense time series of satellite images will be more and more available: Formosat-2 was launched in 2004 and ESA is now preparing the Sentinel-2 dual satellite missions, which would provide with one image every 5-day over the entire Earth at a decametric resolution (launch planned around 2015). There is thus a need to use what is already available in order to prepare the exploitation of these data which would be available at the global scale in a near future. In addition, the main concern of our paper is to analyze the potentiality of ASAR imagery for the monitoring of irrigation and soil moisture. In this sense, Formosat-2 images should just be considered as a material, and the issue addressed in this paper is not that of the temporal density of optical data. Many papers have been already written on this topic (e.g. Hadria et al. in 2006 for our team).

A sentence mentioning the future projects of high resolution and high repetitivity sensors in the optical domain has been added to the introduction:
"The continuity of combined high resolution and repetitivity data sets in the optical domain is insured in the near future by the planned launch of Sentinel-2 dual satellite missions (ESA, 2007, cited in Hagolle et al. 2008)." [Lines 45-48]

Having such availability of a time series of optical data, the whole approach is still based on looking for time evolution of NDVI, to retrieve Green Leaf Area index (GLA) by using an empirical relationship with NDVI. This information is used together with the SAFY model to drive the overall crop temporal evolution model, by using GLA as the driving variably to constraint the model parameters describing such crop temporal evolution. Is there another way of constraining the model by using more information from optical satellite data beyond NDVI? The limitations of NDVI are well known, then some argument must be given to justify that in this case the information provided by NDVI is enough to track the temporal evolution with the required accuracy.

NDVI provided by Formosat-2 is used to calibrate the SAFY model through the inversion of one biophysical variable (GLA). The SAFY model has been developed to provide results at a regional scale using a minimal number of data input and simple formalism. In addition, the NDVI-GLA relationships are well-known to be accurate and robust over annual crops. In this paper, it is shown that the accuracy of the relationship is higher than the error on GLA measurement using indirect method. This approach has been shown to be specifically adapted to perform regional analysis based on remote sensing data. In particular, our previous studies on wheat crops in Morocco as well as on maize and sunflower on southwest of France have shown that this methodology based on the SAFY model and time series of high spatial resolution satellite images provides with accurate simulations of GLA, dry above-ground biomass (Duchemin et al. 2008b, Hadria et al. 2009, Claverie et al. 2009, the latter reference being added in the revised version, the two first were already cited in the first version of the paper). There are undoubtedly many other methods that could be tested in order to better control the model through parameter identification or data assimilation using the Formosat-2 data reflectances or other vegetation indices. However, the reviewer is invited to consider the two following points: (i) regarding the quality of the NDVI-GLA relationships obtained in this study, it is not sure that that the use of other indices or non-linear regression approach (neural network) will improve the results and,(ii) more advanced approaches based on a radiative transfer model and a data assimilation method would require additional information (e.g. chlorophyll contents of the leaves, geometrical characteristics of the canopy) and a careful calibration of the observation operator.

In this study, we were interested in a regional analysis (8x8 km² study area) under the perspective of developing a robust algorithm, thus we decided to apply the most simple method (see the end of introduction lines 77-78).

Given all these arguments, we may consider there is no need to address neither the question of NDVI-GLA relationship in our paper nor the issue of the model set up. In addition, we would mention that the methodology is detailed in a paper that focus more on agronomical purpose (water-use-efficiency of wheat crops), which have been submitted to Remote Sensing of Environment. This paper is available to the reviewers and the editor upon request.

Concerning ASAR data, the processing is quite standard, using finally HH polarization to retrieve topsoil moisture, as the best option among the different polarizations available, for such purpose. The empirical relationship used to retrieve soil moisture from radar data is extremely simple, just a linear relationship. The two coefficients of the linear relationship are derived from extreme values of soil moisture, and extreme values of HH backscattering, but it is still a linear relationship. Such linear scaling of radar variations to moisture variations seems a rather simple assumption, as all such relationships tend to be non-linear, with saturation in the signal. The linear approach assumes authors are looking for a limited range of signal variability, which is consistent with the idea that the method is applicable only in some stages of crop evolution, but this aspect need some explanation in the paper.

As far as we know, the fact that the radar signal could saturate when the soil is very moist is still questionable. If required, we may perform additional tests of non-linear relationships, but this will require time. Furthermore, there are many papers in the scientific literature relying on linear relationships for different types of land surfaces (Champion and Faivre 1997, Le Hegarat et al. 2002, Holah et al. 2005), including wheat (Ulaby et al. 1979) showing accurate top soil moisture retrievals. The paper presented by Dobson and Ulaby (1986) is particularly interesting because the linear relationship provide more accurate results with vegetation compared to one established for bare soil (correlation coefficient r of 0.92 with various crops, and 0.85 for bare soil). A sentence has been added in the paper on this point [lines 374-375], with all these references cited.

The main problems with this paper come from the somehow controversial results, opposite to the evidences reported in previous studies.

In our study, Section 4 shows that the radar signal is sensitive to variations in top soil moisture even when wheat canopy is fully developed. As specified in the text, these results are consistent with other studies made on wheat. Brown et al (2003), as well as Mattia et al (2003) have found an increasing of several dB when soil is moving from dry to wet. Ulaby et al (1979) that showed that the difference in the radar signal between wet and dry conditions is several dB at 4.25 Ghz, and that this difference was observed for viewing angles between 0° and 60° for a 1 m height wheat crop. This sentence was added in the revised version [lines 326-329].

Although the modeling of physical processes that may explain our results is not the subject of the paper, some hypotheses are mentioned below in the answers to questions a), b) and c). They are presented and have to be considered as possible explanations but we agree that understanding of the scattering process for vegetated surfaces is still challenging (e.g. Stiles and Sarabandi (2000), Picard et al. (2003)).

This may be due to the particular characteristics of the study site, or most probably to the particular methodology used in this case, where the radar data are analysed using the results of a model fitted to inputs derived from optical data.

We agree that the site is specific (see below our response to point (e)). This was already mentioned in the conclusion [lines 499-501]. However, we do believe that the methodology used, though based on simulations, is not specific and is suitable to support the main findings of this paper (see the Section 3.2 : Model set up and evaluation). In addition, we thought interesting to show results in the very adequate conditions (surface homogeneity, topography, climate…) underlined by the reviewer. The errors in these conditions may then be considered as a reference. Of course, adaptation would be necessary to use this methodology on other sites where these conditions are not totally met. A sentence has been added in the revised version to underline this [lines 527 – 529].

In any case, it is somehow surprising to observe the following results:
(a) At the beginning of the agricultural season, when the soil is mostly visible as the fractional cover by vegetation is still very low, there is no relationship between the radar backscattering and the soil moisture. The expected behaviour would be that the sensitivity of radar signal to soil moisture would be better when fractional vegetation cover is low, with the possible complication coming from soil roughness variations as well. The authors attribute the variability to canopy water content instead of soil roughness, but no relationship to soil moisture changes. However, if in such stage of crop evolution the rather signal is more sensitive to canopy water content than to soil conditions, it will be difficult to believe that later on when the canopy biomass increases and thus has a much larger canopy water content, the sensitivity of radar signal to soil moisture will however then increase. It is understood that the reported in

the paper are the observed results, but it must be some credible explanation or justification for such results.

Yes, this result on the radar signal is somewhat complex to understand, but not doubtful. Indeed, at the beginning of the growing season (sowing to emergence phase) fields progressed from bare soil to a state with bare soil and vegetation (planting dates collected spread from the 11/25/2007 to the 01/08/2008). Furthermore, the soil moisture is rather homogeneous and moderate since the last irrigation was performed before sowing and since a significant rainfall event occurred at the end of the year 2007. Given these facts, it is expected that the signal should be first sensitive to the vegetation, and specifically its biomass water content (BWC). Indeed, even if the leaf density is low at emergence time and just after, its water content is high (larger than 80% of the total above-ground biomass), while the top soil moisture was moderate (around 20% at 5 cm depth at the beginning of Januray 2008 according to our TDR measurements). That's why we present in the Fig. 9 the behavior of the radar signal in relation to BWC, which appeared to first increase, then saturates, decreases and still stable around -7 dB when BWC reached about 5 t ha^{-1}. This figure allowed to confirm that there is an actual sensitivity of the signal radar to BWC.

(b) For mature and senescent canopies, one would expect that since the canopy has lost most of the water content, then the radar signal will become more sensitive to the soil background, but the method described in this paper provides poor results at the end of the agricultural season. The explanation given is the presence of dry litter after harvest, but the arguments are not very solid to explain such behaviour.

As it was stated in the paper [lines 431-433], the surface is in very various states (more or less advanced senescence, plants completely dry or harvested, soils before and after the harvest). This likely explains the poorer performance of the inversion method at this time.

(c) The best results in terms of correlation between topsoil moisture observations and the inversion results are obtained for intermediate case, when vegetation cover is high enough, but before the start of senescence, for biomass water content larger than 5 t/ha. This is again a rather surprising result, because one would expect that at C-band frequency the presence of a significant vegetation layer would prevent retrievals of soil moisture. Some explanation for this behaviour must be given. Either this is due to the particular method used in this case (the usage of optical imagery to fix the model to which radar data are later inverted), or due to the peculiar behaviour of the given study area.

The results presented in the paper may seem surprising since the method works best when plants are in the growing phase, and the ground is therefore covered. However, we do believe that our methodology is sound and that these results are very interesting since they are obtained from a lot of fields (about 180). Indeed, our method account for the biomass water content levels that affects the variability of the radar signal. It is such a kind of 'normalization' to get off the impact of the vegetation. In particular, the attenuation caused by vegetation growth (visible on Fig. 7) is accounted for in a large part though the biomass water content level. We could thus be confident in our finding that the radar signal is still sensitive to soil moisture even under well developed wheat crops, in coherence with the previously-mentioned studies.

(d) The independence of soil moisture retrievals from soil roughness conditions and varying incidence angle is reported as a nice feature of the algorithm, but the reason for that should be better explained. This is probably a feature of the study area, or the way the retrievals are implemented in this case.

The independence of soil moisture retrievals from soil roughness conditions is explained in the Section 5, paragraph 1 [lines 357 - 362]. Roughly the same agricultural practices were used over the whole study area. In particular, it is thus reasonable to state that for wheat crops at a same stage of development (accounted for though the biomass water content separating growing and senescent phases), the soil roughness is almost the same from one field to the next.

According to the independence of soil moisture retrievals from incidence angle, we specified in Section 5 [lines 365 - 367] that the method was set up for each ASAR viewing conditions. This results on ten independent and calibrated relations between backscattering coefficient and biomass water content (presented in Table 2) such as the one shown in Fig. 7. This was possible as numerous Envisat images were regularly acquired during the whole wheat phenological cycle. In this way, no angular normalization was performed, and so each image configuration keeps its sensitivity to surface parameters. In these conditions, as shown in Table 2, the radar sensitivity to top soil moisture (distance between the upper and the lower edge of the trapezoid) decreases as incidence angle increase which is in agreement with the radar physics as documented by Ulaby.

(e) The reported relation between soil moisture evolution and irrigation events also need some better description. The anomalies reported for fields 1 and 3 seem to indicate some potential problems with data collection and / or heterogeneous soil behavior in the area.

Even if we paid careful attention to data collection during this experiment, the field data set was very important at the end. Land-use was collected on an 8x8 km^2 largest area, while agricultural practices were collected on 114 fields over the 4x4 km^2 central zone from November to June. This second data set represents 114 fields cultivated with 8 different crops. Irrigation was estimated after collecting schedules (opening and closure of gates on where water flow before reaching the field) and gathering information from farmers. It is possible that error has occurred during data collection. This was stated in the paper, Section 5, at the end of paragraph 6 [lines 459-461].

Since the idea of such methodologies based on remote sensing data should be to extrapolate them to larger areas or to other geographical sites, the limitations in the applicability of such methodology for an area with large fields, flattened and cropped with modern mechanized agricultural practices, should be properly explained in a more specific way.

The study presented takes advantage of the characteristics of the study area (flat terrain, same agricultural practices, large fields...), and therefore, it is clear that the generic aspect of the method is questionable. In this objective, it would be necessary to apply the same methodology to new sets of independent data acquired on another site. It is noteworthy that in most previously-mentioned studies, the robustness is rarely mentioned, even though the site dependence is generally important.

The study presents a method based on the combined use of SAR and optical images acquired over the agricultural region of Yaqui, the most important wheat production area in Mexico. The retrieval of soil moisture takes advantage of the characteristics of the study area, simplifying the soil description by a set of invariant characters. The limits of the method are therefore based on this assumption; identify geographical entities where culture conditions are similar in order to simplify the soil description.

This is now clearly stated in the conclusion of the new version of the paper [lines 527-529].

Some minor aspects also require attention:
(a) Equation (1) and (2) are general for ASAR data. Authors must give the actual values of the different variables (NLeff, Npaz, Npra, etc.) for this particular case of this study, otherwise such equations are useless.

The actual values of the different variables were added lines 191-209.

(b) In the abstract and later in the text the absolute accuracy in retrieving soil moisture is of 9% (0.09 m3 m-3), with 35% as relative value. Such relative values should be explained.

Relative value was computed as root mean square error (RMSE) divided by the mean of observed values, and express in percent. This explanation was added in Section 3.2, second paragraph.

(c) In Section 2.2, second line, "agricultural pratices" should be "agricultural practices".

Done. Thanks.

(d) The relationship between simulated soil moisture and measured soil moisture plotted in Figure 8 shows some systematic behaviour, not just random around the 1:1 line but some kind of curvilinear relationship, with overestimation for intermediate values. The simple linear scaling approach between C-HH backscattering and soil moisture is probably the reason. A plot of the residuals would probably be better to show such systematic deviations.

Indeed, the bias for moderate to high values of top soil moisture is clear. We discussed this above and justify the use of a linear relationship (page 3 of this document).

(e) Figure 9 shows a weak dependence of HH backscattering on vegetation water content. A similar plot with VV backscattering would help to understand the effect of vegetation signal (HV not available in this case).

A preliminary analysis was performed. It showed that the sensitivity of the radar signal to irrigation is lower in VV and in HH backscattering.

(f) Figure caption for Figure 10 is somehow unclear, particularly when referring to rainfall lines in the plot (along the y-axis?).

Thanks. This was corrected in the revised version.

References

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Stiles, J. M., Sarabandi, K. & Ulaby, F. T.: Electromagnetic scattering form grassland – part II: Measurement and modeling results, IEEE Transactions on Geoscience and Remote Sensing, 38, 349-356, 2000.