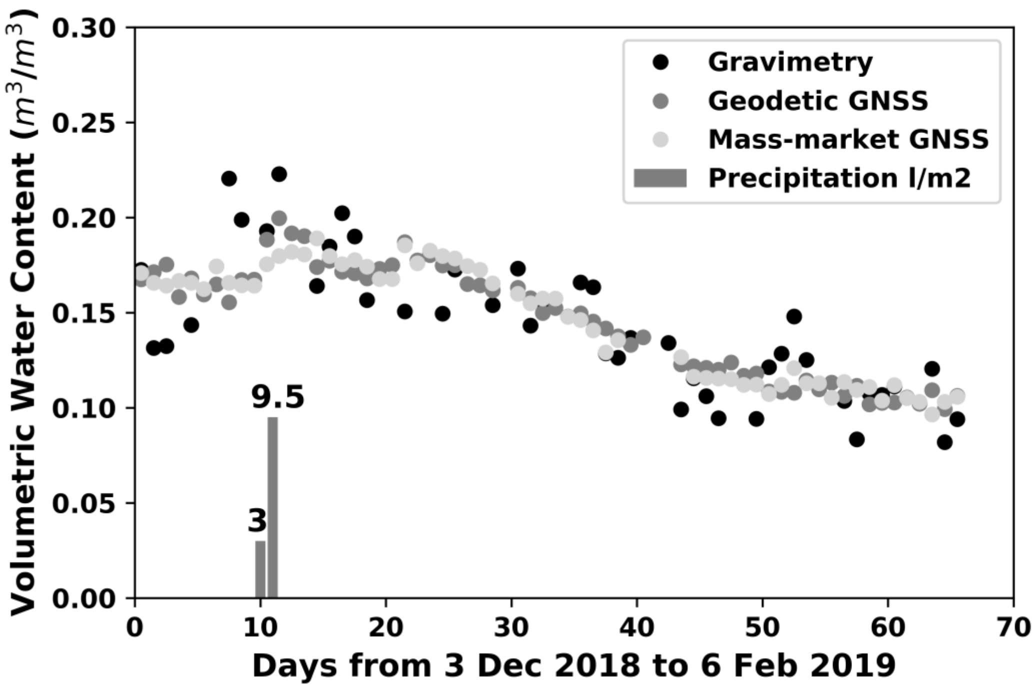
General comments

Martin et al. promise a study regarding the multi-constellation GNSS interferometry for soil moisture retrievals. The study does not live up to its title, since in fact, multiple single constellations are analyzed, yet there is no integration of data from the different constellations. Because of this, the current study merely seems a replication of a well-known methodology with little novelty. As expected, the authors do indeed show reasonable agreement between soil moisture estimated from GNSS interferometry and in situ measurements. I found the paper poorly structured, the statistical analysis incomplete, and the discussion lacking depth. The findings of this study are at best incremental.

Answer:

The proposed solution is based on the individual study of each satellite constellation, obtaining equivalent results for the three constellations, so the reviewer is right in saying that there is no integration of constellations. A new figure (which can be seen below) will be introduced in the final version of the manuscript with the combined solution of the three constellations as the average of the sum of the respective solutions, this new figure can be considered as a combined multi-constellation solution.



New Figure. GNSS (GPS+GLONASS+GALILEO combination) comparison of daily soil moisture. The results of the geodetic and mass-market antennas are compared with the reference gravimetric data set.

A restructuring of the document will be carried out and the statistical study and discussion will be completed (see below as an answers to other suggestions).

The most important novelties of the research are technological, but we think they are important for the actual implementation of the technique in the agricultural sector: The introduction of GALILEO and GLONASS constellations, produce a much larger sample set of observations around the antenna, and, specially, the introduction of mass-market GNSS sensors as the basis for the technique, which will greatly reduce the costs making the technique viable.

Specific comments

- From figure 2, can you please explain where exactly the reference soil moisture measurements were taken in reference to the ellipses around the antenna? How did you account for spatial offsets in the order of meters between the reference and GNSS soil moisture measurements?

Answer:

The results presented reflect the average value of soil moisture around the GNSS antenna per day obtained from all tracks of all satellites per constellation or using the three constellations as an average, so, there is no offset to consider, the average values obtained from GNSS technology have been compared with the in situ samples obtained in the soil (one per day except weekends). No bias in the results can be expected since the ground around the antenna is very homogeneous.
Nonetheless, the location of the samples will be included in the Figure 2 as is suggested by the referee:

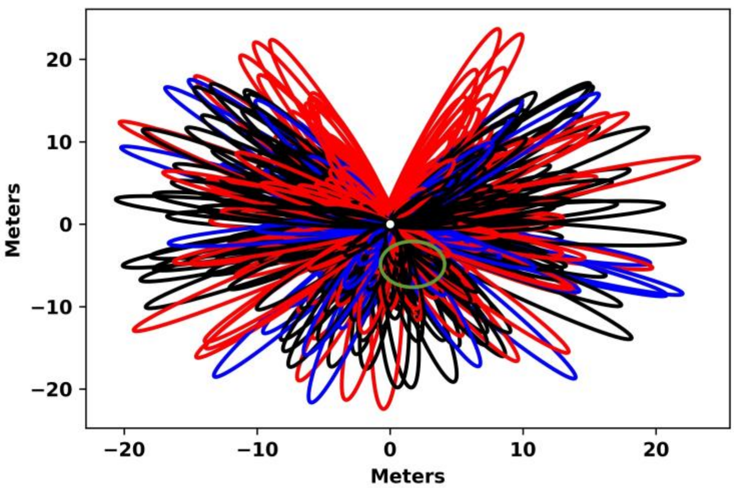


Figure 2. *GNSS Fresnel ellipses around the geodetic antenna during one of the observation days. GPS constellations satellites are shown in black, GLONASS satellites are shown in red, and GALILEO satellites are shown in blue. Green circle is the location where soil samples have been taken.*

- P1L21: Correlation coefficients are not expressed as percentages

Answer:

It will be changed in the final version of the manuscript.

- P1L27-28: The native resolution of the SMAP passive sensor is approximately 36 km. With no active sensor, the 9 km product is created by integrating non-SMAP data sources. Therefore, 36 km is the more correct resolution to mention in comparison with SMOS. Sentinel-1 sensors have a revisit time of 12 days. 2 Sentinel-1 sensors are in orbit, which decreases the revisit time. The spatial resolution is in the order of 10s of m. Please modify.

Answer:

This will be included in the final version of the manuscript.

- P3L82-84: Please elaborate on what L1, E1, L2, E5 and L2C are for non-specialist readers.

Answer:

The radio-signal structure of GPS, GLONASS and GALILEO systems are similar. Different carrier signals in the L-band are broadcast, L1 and L2 corresponds with the two main frequencies of the signal emitted from the GPS satellites and E1 and E5 with the two main frequencies of the signal emitted from the GALILEO satellites. In contrast to GPS and GALILEO, GLONASS satellites transmit carrier signals at different frequencies from a basic L frequency (explained in the section 3.1 of the manuscript).
L2C corresponds to the Civil L2 signal of the block satellites IIR-M and IIF of the GPS constellation, available only since 2005 when the first block IIR-M was launched. This signal is designed specifically to meet commercial needs, which increases robustness of the signal, improve resistance to interference, and improve accuracy (Leick et al., 2015).

This explanation will be included in the final version of the manuscript.

- P6L166-167. Figures 7-10 portray very little additional information in reference to Figures 5-6, and the differences with Figures 5-6 are not well described in the text.

Answer:

Our first idea was to include a complete example for each constellation for a better understanding of the results. This is the only difference between the graphs, so, in comparison, they should be very similar since they show a good complete trace of a satellite. However, as is explained in the discussion section, the SNR values for GLONASS and GALILEO present a systematic bias of about 3-5 db-Hz between the geodetic and mass-market antennas (Fig. 7a and 8a and Fig. 9a and 10a). This effect *has an impact in the range of the reflected signal. This explanation can be included in the processing section as a justification for the inclusion of the figures or, as suggested, figures from 7 to 10 can be eliminated in the final manuscript including in the text something like "…the same results can be obtained if a GLONASS or a GALILEO satellite is plotted".*

- Can you please elaborate on the comparison between the GNSS-derived soil moisture and reference datasets? And on the difference between the results from the geodetic and mass-marked antennas. A statistical analysis could include simple linear regression, from which deviation from the 1:1 line and goodness-of-fit values could be discussed, among others. The statistical analysis is poor and incomplete.

Answer:

Table 1 is completed with the information of the GNSS results (that is, including the three satellite constellations combination), and, also, including new statistical scores.

MAE is the mean absolute error, RMSE is the root mean square error, mean and Std. are the mean and the standard deviation of the differences.

The Pearson correlation coefficient can be used to summarize the strength of the linear relationship between two data samples. Spearman correlation can be used to summarize if two variables are related by a nonlinear relationship, such that the relationship is stronger or weaker across the distribution of the variables.

Pearson and Spearman correlation are equivalent between Geodesic and Mass-market antenna for every constellation and comparing the constellations. These means that a lineal relationship can be considered between the soil moisture results obtained from all GNSS antennas and the sample observations.

If we consider the results obtained for every constellation independently, equivalent results between geodetic and mass-market antenna is obtained for RMSE, MAE, Mean and Std., showing the good performance of the mass-market antenna.

The worst results in terms of RMSE, MAE and Std. were obtained for GALILEO constellation, probably because there aren't as many satellites in the constellation as the GPS and GLONASS constellations have. GLONASS constellation offers slight improvement in terms of RMSE, MAE and Std. results in comparison with GPS, whose range of values appears more compressed for both the geodetic and mass-market antennas, probably because GPS constellation, in the moment of the observations, had three different satellite blocks (blocks IIR, IIF and IIF) with different capabilities, and GLONASS only two (blocks M and K).

However, the ranges of RMSE, MAE and Std. considering GPS, GLONASS and GALILEO constellations (both geodetic and mass-market antennas) are less than 0.01 m3/m3 and less than 0.15 for Pearson or Spearman correlation, so we can consider that the *three constellations produce similar V_{GNSS} values, regardless of the type of antenna used.*

This last conclusion opens the possibility of using the three constellations in combination as the average value obtained from the value of each of the constellations. The last two columns of Table 1 show the statistical summary of this combination for both the geodetic and the mass-market antenna, where it can be seen that the values obtained are equivalent to those of the previous columns.

***Table 1**. Statistical summary of the soil moisture estimates from the GPS, GALILEO and GLONASS constellations with the reference (in situ) values. GNSS is the combination of the three constellations. RMSE is the root mean square error, MAE is the mean absolute error and Std. is the standard deviation of the differences.*

	GPS vs. in situ		GALILEO vs. in situ		GLONASS vs. in situ		GNSS vs. in situ	
	Geodetic	Mass-market	Geodetic	Mass-market	Geodetic	Mass-market	Geodetic	Mass-market
RMSE (m^3/m^3)	0.025	0.026	0.028	0.024	0.020	0.020	0.022	0.022
Pearson correlation	0.77	0.72	0.75	0.76	0.83	0.84	0.80	0.81
Spearman correlation	0.78	0.75	0.80	0.80	0.82	0.85	0.78	0.81
MAE (m^3/m^3)	0.020	0.021	0.023	0.020	0.016	0.016	0.017	0.018
Mean (m^3/m^3)	0.002	-0.003	-0.001	0.005	0.000	0.002	0.001	0.001
Std (m^3/m^3)	0.025	0.026	0.028	0.023	0.020	0.020	0.022	0.022

- P6L175-176. The discussion starts with a table of results. Please move this to the Results section. Can you in the Discussion section elaborate a bit more on your findings, for example why did the GLONASS retrieval outperform the other retrievals?

Answer:

All sections will be restructured in the final version. The answer to the GLONASS constellation can be read in the previous comment.

- The paper is poorly structured: parts of the Introduction (including figures) would fit better in the Methods section, the Results has preprocessing and processing headers but not really results, some results are given in the Discussion section.

Answer:

Thank you very much for the comment. All sections will be restructured in the final version.

- It is unclear to me why the authors wrote an opening paragraph covering spaceborne soil moisture retrievals when the paper covers another topic.

Answer:

If the GNSS-IR technique is considered as another remote sensing technique for estimating soil moisture, this paragraph makes sense in the state-of-the-art section as a reference to locate the differences of the GNSS-IR technique in terms of resolution and temporal latency with respect to the images obtained by Earth observation satellites. In the final version of the manuscript the concept that the GNSS-IR technique should be considered within the remote sensing techniques will be written.

- It is unclear to me why the authors did not integrate the BEIDOU constellation.

Answer:

Because the receivers used in the experiment could not decode the information of the BEIDU satellites. This will be added in the final version of the manuscript.

Comments in the manuscript

General answer:

All spelling, syntactic and grammatical errors will be corrected in the final version.

-Section 2.1. What is meant with 'our' sector? In addition, most of this paragraph is not relevant to the study.

Answer:

Sorry, 'our' sector means agricultural sector. The paragraph describes the activities of the center, since, on its website (https://www.fundacioncajamarvalencia.es/es/comun/), they cannot be read in English.

- Please explain what NMEA GSV is for non-specialist readers.

Answer:

NMEA is an acronym for the National Marine Electronics Association. Today in the world of GNSS, NMEA is a standard data format supported by all manufacturers to output measurement data from a sensor in a pre-defined format in ASCII. In the case of GNSS, it output position, velocity, time and satellite related data (for the constellations that the antenna can decode). There are quite a few NMEA messages or sentences, not just one. Specifically, GSV sentences provide integer numbers for elevation, azimuth and signal-to-noise ratio. This explanation will be added in the manuscript.

-What is meant with 'uncut'?

Answer:

No signal interruptions, it will be changed in the final version of the manuscript.

-GPS 23

Answer:

GPS satellite number 23