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Evaluation of crop development stages with TerraSAR-X backscatter signatures (2010-12) by using Growing Degree Days

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ABSTRACT

TerraSAR-X images have been tested for agricultural fields of corn and wheat. The main purpose was to evaluate the impact of daily temperatures in crop development to optimize climate induced factors on the plant growth anomalies. The results are completed by utilizing Geographic Information Science, e.g. tools of ArcMap 10.3.1 and databases of ground truth and meteorological information. Synthetic Aperture Radar (SAR) images from German Aerospace Center (DLR) are acquired and the field survey datasets are sampled, each per month for three years (2010-2012) but only for the crop seasons (April-October). Correlation between SAR images and farmland anomalies is investigated in accordance with daily heat accumulations and a comparison of the three years' SAR backscatter signatures is explained for corn and wheat. Finding the influence of daily temperatures on crops and hence on the TerraSAR-X backscatter is developed by Growing Degree Days (GDD) which appears to be the most suitable parameter for this purpose. Observation of GDD permits that the coolest year was 2010, either rest of the years were warmer and GDD accumulated in 2011 was higher as compared to that of 2012 in the first half of the year, however 2012 had rather more heat accumulation in the second half of the year. SAR backscatter from farmland depicts the crop development stages which depend upon the time when satellite captures data during the crop season. It varies with different development stages of crop plants. Backscatter of each development stage changes as the roughness and the moisture content (dielectric property) of the plants changes and local temperature directly impacts crop growth and hence the development stages.

KEY WORDS: SAR backscatter, TerraSAR-X, Growing Degree Days (GDD), plant phenology.

1. INTRODUCTION

Agriculture is a basic ingredient for building economy of a society and its production is therefore required to be optimized. Increase in the requirement for long-term use of natural resources along with a price effective and limiting use of fertilizers and pesticides oblige the engagement of modern technologies in agriculture and environment.

The use of remote sensing techniques for data assimilation to crop management and crop yield forecasting models has been greatly increased in the last two decades.¹ This is because the remote sensing data shows many advantages over conventional methods in terms of economic investment, time, and spatial and temporal confines of the analysis.² As agricultural yield increases, additional data about the fields is required in order to improve monitoring and management systems. Because of the immense size of the observing area and the periodical data collection, remote sensing satellite data is considered to be a very important agricultural data supply.³

Electromagnetic response of the different parts of a crop cover not only depends on the wavelength used for observation, but it also varies because of the season, angle of incidence of the sensor, crop's features, illumination intensity, meteorological phenomenon and topography among other external factors.

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In this regard, Pinter et al. (2003) concluded that a significant challenge for agricultural remote sensing applications is to make the spectral signals originating with a plant response to be isolated to a specific stress from signals associated with normal plant biomass or the background noise that is introduced by exogenous non-plant factor.⁴

In fact, there are a number of types of remote sensing data available for crops' monitoring. In this perspective, optical remote sensing data is among the most used. Many relevant applications of this type of data for several sensors have been reported to have noteworthy achievements due to the results reached from the physical understanding of the crops' responses for optical bands.¹ Nevertheless, due to the necessity of the daylight for illuminating the objects, the use of this kind of data is limited. It is hard to provide data on a regular basis using optical images because of cloud cover.

In comparison to the optical remote sensing, the SAR images for monitoring the vegetation are still not extensively applied for educational as well as industrial objects. Therefore, some related acquaintance about the impact of the vegetation conditions on the backscatter is required for using the SAR images to manage and monitor the agriculture resources.⁵ Synthetic Aperture Radar (SAR) is a common active sensor for microwave, this sensor is called active because of the usage of its own energy source to irradiate and measure the difference in power between the transmitted and received electromagnetic radiation. The radar backscatter energy hinges on radar, target and external factors. Frequency / wavelength, polarization and angle of incidence are the principal factors that define the features of the radar backscattering, and every one of these have a significant influence to be considered for assessing the interaction between the radar signal and the target. As the angle of incidence declines, the probability of greater backscatter increases, predominantly as the target becomes smoother.⁶

Effects of the target are directly related to the radar itself. Likely, when we consider crops, the impact of radar parameters on radar backscattering varies depending on the dielectric properties (water content), orientation of leaves, or leaf geometry (shape and size). Furthermore, the external factors could also be a source of change in the radar backscattering, for example influence of seasonal variability on crops and soil features under the crops cover.⁷ For instance, water saturated soil is a strong reflector whereas dry soil has low radar reflectivity which results a decrease in the backscatter.⁶ The higher wavelength corresponding to lower frequency penetrates deeper through crops and soil, therefore lower frequency radar images are better for the studies of soil under vegetation, higher frequency radar waves are preferred for crops monitoring.⁸ That is why, for crop studies, microwave X-band (2.5cm-4cm) is more suitable than C-band (4cm-8cm) and L-band (15cm-30cm).

Growing degree-days (GDD) is a temperature based approach that is often used as a meteorological indicator for evaluating crop development and it is a trustworthy inferrer of the development of many crops throughout the growing season. This development under fields' environment can be described using a unit called "cumulative growing degree days". Cumulative growing degree-days include daily average temperature in centigrade over a timeframe, usually from seeding to the day of interest. Nevertheless, these average temperatures are subtracted from a particular temperature called as base temperature. Base temperature is a critical temperature at or below which the crop development is zero and there is no or little growth below this temperature.^{9,10}

Each region has its individual equipment of natural features of geography, geology, soils, water balance and climate which differentiates it from the others. As the Baden-Württemberg has regions with different altitude and terrain characteristics like the Black Forest and Swabian Alps, the phenological stages of crops are different in various parts of the state. In this region, there are different situations of climate in terms of precipitation and temperature as compared to rest of the world which directly influence farmer's activities in the fields with respect to seeding and harvesting time. For this reason, notwithstanding the intention, the use of temperature interpolations, for getting precise local temperatures from measurements of the available weather stations becomes complicated and hence not very expedient.

2. AIMS AND OBJECTIVES

Main aim of the study includes:

- the comparison of the backscatter values with the fields' ground truth information
- finding of an appropriate meteorological approach for the analysis of crop morphology

Analysis of backscatter values from TerraSAR-X remote sensing images is pursued. The backscatter signatures of corn and wheat were derived for three years on a monthly basis and the correlation between these SAR images and the annual

variations in growing conditions, particularly in accordance with heat accumulations, is investigated and a comparison of the three years' SAR backscatter signatures is completed for both of the crops.

Specific objectives are as follows:

- generating backscatter signatures for all the fields of corn and wheat within the test site
- elaborating the behavior of corn and wheat crops according to their specific backscatter values
- exploiting some techniques to incorporate the daily mean temperatures for the calculation of amount of heat consumed by the plants for their development and growth
- finding the effect of daily heat accumulations and precipitation on the SAR backscatter of corn and wheat
- interpolating the average air temperature in order to get good estimation of the heat accumulations on local scale within the test site

3. STUDY AREA

Study area is located in the German state Baden-Württemberg (BW) at a distance of about 50 km from Stuttgart, near Mössingen in the district of Tübingen. The extent of the scene acquired by TerraSAR-X is quite larger as compared to the concerned test site.

Figure 1. Spatial Location of the SAR Cover¹¹

Approximate coordinates of SAR scene, starting from upper-left corner in clockwise direction, are 48°31'55"N 8°49'33"E, 48°28'31"N 9°15'42"E, 48°17'21"N 9°11'54"E, 48°20'41"N 8°46'15"E. The area covered by the SAR-images has elevation values ranging from ~380m to ~880m but the concerned test site area has an estimated average elevation of 800m (© Google Earth 2011).

Figure 2. Locations of the observed fields¹¹

4. METHODOLOGY

In the acquisition, VV polarization with Stripmap imaging mode was used. The images were saved in tiff format with a radiometric resolution of 16 bits. The images were acquired from right looking and descending orbital directions with ground cell resolution of 3m. The TerraSAR-X captures in strips so the scene for the study area, strip_006, has been provided with swath width of 30 km and incidence angle range of 27.19° to 30.23° . These images were also Enhanced Ellipsoid Corrected (EEC) and Spatially Enhanced (SE) which provide the highest square ground resolution. Data preparation in this study includes SAR images unzipping and their clipping processes and managing the data of temperature and precipitation. The data preprocessing includes the radiometric calibration of the SAR data and vector data projection system transformation. The complete radiometric calibration process includes firstly the extraction of the local incidence angle (θ_{loc}). Then it has calculation of the beta naught (β°) which is the radar brightness in slant range and finally the calculation of the gamma naught (γ°) which is nothing but the β° projected on the unit areas perpendicular to the line of sight via $\tan(\theta_{loc})$.¹²

Figure 3. Stepwise study procedure

SAR data post processing includes SAR data and GIS data processing and calculation of Growing Degree Days (GDD) for each crop type. The maximum and minimum centigrade temperatures and the base temperatures in centigrade for each crop culture were added in excel columns which were then manipulated according to the formula in Eq. 1.

$$GDD = \frac{T_{max} + T_{min}}{2} - T_{base} \quad (1)$$

$$\text{If } T_{average} = \frac{T_{max} + T_{min}}{2} < T_{base} \text{ Then } GDD = 0$$

Where, T_{max} and T_{min} are the daily maximum and minimum temperatures respectively and T_{base} is the base temperature which is different for different crops. This is a critical temperature at or below which the growth of the crop is stopped.¹⁰ These GDDs were calculated and saved in the corresponding excel column for the complete three years (from Jan. 01, 2010 till Dec. 31, 2012). These calculated degree days were then accumulated for whole of the years. This was executed in a way that every day's GDD accumulation was an integration of all the GDDs from Jan. the 1st till the day of interest.

5. DATA

Availability of the acquired and hence the processed data are described in Table 1 in which every data type is presented in columns. In the 1st column there exist the months of crops' seasons of all the three years whereas in the 2nd column acquisition dates of the corresponding SAR scenes are shown. The boxes with cross inside are representing the unavailability of the corresponding data. From the 3rd column onward there exists the information about the field's GIS data like number of fields under consideration, whether the GIS data projection was transformed to WGS 1984 or not, whether the image statistics of crops' fields were calculated from all the available SAR scenes or not and which month's GIS data (fields' geometry) was used in the absence of some GIS data, this is shown in parentheses in 5th column under fields statistics. Temperature and precipitation (prior to SAR acquisition time) values were acquired from a nearest available weather station with a similar height as that of the test site.

Table 1. Availability of acquired and processed data.

Month, Year	SAR Data Acquisition. Date	GIS Database	Projection Transformation	Fields Statistics
Jun, 2010	7-Jun	369	Yes	Yes
Jul_A, 2010	10-Jul	×	×	Yes(Jun, 2010)
Jul_B, 2010	1-Aug	×	×	Yes(Jun, 2010)
Aug, 2010	×	×	×	×
Sep, 2010	×	×	×	×
Oct, 2010	28-Oct	369	Yes	Yes
Apr, 2011	10-Apr	372	Yes	Yes
May, 2011	14-May	372	Yes	Yes
Jun, 2011	5-Jun	372	Yes	Yes
Jul_A, 2011	8-Jul	372	Yes	Yes
Jul_B, 2011	30-Jul	372	Yes	Yes
Aug, 2011	×	372	×	×
Sep, 2011	×	372	×	×
Oct, 2011	15-Oct	372	Yes	Yes
Apr, 2012	19-Apr	×	×	Yes(Jun, 2012)
May, 2012	22-May	×	×	Yes(Jun, 2012)
Jun, 2012	13-Jun	373	Yes	Yes
Jul_A, 2012	5-Jul	373	Yes	Yes
Jul_B, 2012	27-Jul	373	Yes	Yes
Aug, 2012	29-Aug	×	×	Yes(Oct, 2012)
Sep, 2012	20-Sep	×	×	Yes(Oct, 2012)
Oct, 2012	23-Oct	373	Yes	Yes

6. RESULTS AND ANALYSIS

The wheat and corn crop types that existed within the test site in all the three years 2010, 2011 and 2012 were successfully monitored. The means of SAR backscatter from these crops for each field were plotted and analyzed for the three years separately. In order to compare SAR backscatter from the crops and heat accumulation on multiannual scale, the backscatter means of means (MM) and GDD accumulations for all the three years have been plotted within a single frame. Additionally, MM is displayed red in the following figures for collective backscatter signature plots.

6.1 Analyses of wheat

There were 55, 32 and 50 wheat fields in the years of 2010, 2011 and 2012 respectively. Information about both fields' conditions and crops was collected for all the wheat fields. These fields were separated into different groups according to their year of existence and seasonal seeding as shown under the following headings.

a) Wheat in 2010

There were a few summer wheat fields but there was winter wheat in most of the fields which was seeded in October 2009 and harvested in August 2010. The means of backscatters from these fields have been plotted separately for both of the seasons.

Figure 4. left: Time versus means of backscatter (γ^0) from winter wheat fields, 2010; right: Time versus means of backscatter (γ^0) of summer wheat fields, 2010

It is not realistic to give collateral SAR backscatter analyses for the whole cultivation season of 2010 due to the unavailability of SAR data for the months of April, May, August and September.

b) Wheat in 2011

There was only summer wheat in the fields of the contemporary test site in 2011. This was seeded at the end of March 2011 and there is a possibility that it was harvested at the end of July or in August. It is not realistic to give collateral SAR backscatter analyses for the whole cultivation season of 2011 due to the unavailability of SAR data for August and September (cf. Figure 5, left).

c) Wheat in 2012

There was only summer wheat in the fields of the contemporary test site in 2012. This was seeded at the end of March 2012 and there is a possibility that it was harvested at the end of July or in August (cf. Figure 5, right).

Figure 5. left: Time versus means of backscatter (γ^0) from winter wheat fields, 2011; right: Time versus means of backscatter (γ^0) of summer wheat fields, 2012

d) Inter-annual comparison of wheat

In Figure 6 and Figure 7, plots of γ^0 means of means (MM) and GDD accumulations for wheat are given for the comparative analysis of different years. The x-axis contains the typical date and there are two y-axes, one is the primary y-axis which contains the calculated GDD accumulation and the other is the secondary y-axis which is showing the values of backscatter, the so called gamma naught. For the purpose of quantitative comparison between different years, only those values of both y-axes have been plotted which correspond to TerraSAR-X acquisition dates. For the fulfillment of these data gaps between the two dates, trend lines (in MS Excel) have been used for displaying the yearly shifts of γ^0 (MM) and GDD. Obviously, there are shifts that can be explained by considering them along the two axes, the x-axis and the y-axis. Along y-axis amplitude of γ^0 changes which depends upon the individual fields' parameters like rows' spacing (soil impact) and dielectric constant (soil moisture in case of open soil or leaf water status). For instance, water saturated soil is a strong reflector whereas dry soil has low radar reflectivity which results a decrease in the backscatter (see section I). Likewise, there is a shift in the monthly trends of γ^0 . This so-called x-shift is due to a shift in the development stages which is directly related to GDD.

Figure 6. Comparison of two years' γ^0 from summer wheat and GDD accumulations for wheat ($T_{\text{base}} = 4.44^\circ\text{C}$)

Hence in Figure 6 and Figure 7, when there are more spaces between the two years' plots of GDD accumulation on a particular SAR acquisition date, more x-shift is observed between these years' corresponding backscatter trends. There is

a clear shift between the backscatter signatures of 2010, and 2012. This x-shift can be explained by the fact that 2012 was a warmer year as compared to 2010 which can be seen by observing the GDD plots of the corresponding years in Figure 6. So it can be concluded that due to the least warmth comparatively, the development in the year of 2010 was late as compared to that of 2012.

A clear shift can be observed between the backscatter signatures of 2010 and 2011 in Figure 7. This x-shift is due to the fact that 2011 was a warmer year as compared to 2010.

Figure 7. Comparison of two years' γ^0 from winter wheat and GDD accumulations for wheat ($T_{\text{base}} = 4.44$ °C)

6.2 Analyses of corn

There were 16, 19 and 21 corn fields in the years of 2010, 2011 and 2012 respectively. Information about both, fields' conditions and crops was collected for all the corn fields.

a) Corn in 2010

In the year of 2010, the corn was seeded in May and harvested in October 2010. The means of backscatters from the corn fields have been plotted and presented in the Figure 8 (top left).

b) Corn in 2011

The corn in the fields of the test site in 2011 was seeded at the end of April 2011 and there is a possibility that it was harvested at the end of September or in 1st half of October. The means of backscatters from these corn fields have been plotted and shown in the Figure 8 (top right).

c) Corn in 2012

The corn in the fields of the contemporary test site in 2012 was seeded at the end of April and harvested at the end of September or in October 2012 (cf. Figure 8, bottom).

Figure 8. top left: Time versus means of backscatter (γ°) from corn fields in 2010; top right: Time versus means of backscatter (γ°) from corn fields in 2011; bottom: Time versus means of backscatter (γ°) from corn fields in 2012

d) Inter-annual comparison of corn

In Figure 9, plots of γ° means of means (MM) and GDD accumulations for corn are given for the comparative analysis of different years. Again clear shifts between the backscatter signatures of corn for 2010, 2011 and 2012 were observed.

Fig. 9. Comparison of Three Years' γ° from Corn and GDD Accumulations for Corn ($T_{base} = 10^\circ\text{C}$)

These so called x-shifts are due to the fact that 2011 was warmer as compared to 2010 and 2012 in the 1st half of the cultivation period which can be seen by observing the GDD plots of the corresponding years in Figure 9. So in the 1st half of the crop seasons, the development in the year of 2010 was late as compared to that of 2011 and 2012 due to the fact that till 22nd July, the year 2010 had the least warmth comparatively. Similarly, 2012 had even slower development rate than that of 2011 but only in the 1st half of the cultivation time because later in July, August and September, GDD of 2012 became more than that of the other two years.

In the same way, the shifts in the backscatter trends for the later part of the crop seasons can be explained. As from the start of July onwards, GDD of 2012 became more than that of 2011 and 2010, so in the later part of cultivation time, the development rate in the year of 2011; was slower as compared to that of 2012 but even faster than that of 2010 before 22nd July and after 16th August. This is due to the fact that from 22nd July till 16th August, the year 2010 had more GDD as compared to that of 2011. All this behavior could be concluded after watching the backscatter signatures and GDD of corn and the shifts in their yearly trends which can easily be identified in Figure 9.

7. CONCLUSIONS AND RECOMMENDATIONS

TerraSAR-X backscatter signatures of corn and wheat were generated for the investigation of the crops conditions which has a direct correlation with the backscatter. Reference curves showing means of means (MM) for both of the crops suggest changes within the backscatter signatures with respect to the time. The following points are concluded by exploiting the available resources.

- The backscatter signature implies the phenology stages, which means every acquired backscatter value implies some particular level of growth and development of the crop plant.
- GDD is a direct measure for the development rate of an irrigated crop which influences the corresponding backscatter values. This is also the idea behind its use in this study instead of exploiting some other approach that incorporates the temperature values e.g. the accumulation of daily mean temperatures only.
- The GDD approach is exploitable in different environments and geographical locations if the local temperature and precipitation information is available.
- Any ordinary temperature interpolation was not very useful due to the complex weather conditions in the vicinity of the test site which has Swabian Alps on one side whereas Black Forest on the other. So it was decided to use temperature and precipitation (prior to SAR acquisition time) values measured by a nearest available weather station with a similar height.
- The accuracy of the implied results can be increased by using optimized temperature interpolations to get more precise local temperatures from measurements of the available weather stations. Similarly there is a need for finding some methods for estimating the occurrence of precipitation and dew (dew point temperature) on local level more precisely. In this way the moisture present on the surface of the leaves during the acquisition time can be estimated.

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