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Crop Height Estimation Based on a Novel Semi-Empirical Model Considering Double-Bounce Scattering Using RADARSAT-2 PolSAR Data

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Abstract

Obtaining precise and rapid crop height is essential to facilitate agricultural production services, field management, disaster monitoring, and yield assessment. With the capability to penetrate vegetation and record vertical structure information, Polarimetric Synthetic Aperture Radar (PolSAR) holds significant potential for application in vegetation height inversion. The Water Cloud Model (WCM) and its enhanced versions are extensively utilized for estimating crop heights from PolSAR data owing to their physical significance and simplicity. However, the method is not practical for stalk crops due to the neglect of double-bounce scattering considerations. Therefore, according to the growth characteristics of stalk crops, a three-component polarimetric coherent backscattering model considering crop target double-bounce scattering is established by simplifying the Random Volume over Ground (RVoG) coherent scattering model. The empirical coefficient is introduced to simplify the model into a semi-empirical for crop height inversion. The suitability of applying the RVoG-B three-component model for crop height inversion at the early stage in corn fields was assessed using Multi-temporal C-band PolSAR RADARSAT-2 data in three polarimetric channels. The results show that the HV channel exhibits superior potential in inverting the height of corn compared with the HH and the VV channels. The results of corn height inversion demonstrate that the RVoG-B three-component semi-empirical model performs effectively in estimating corn height, with its inversion accuracy having an RMSE ranging from 11.66cm to 24.51cm. This study demonstrates the potential application of the RVoG-B three-component semi-empirical model for inverting crop height at the early stage dominated by double-bounce scattering.

1. Introduction

Crop height serves as fundamental data for assessing crop growth, predicting yield, and monitoring health. Obtaining crop height rapidly and accurately is crucial for precise agricultural management and enhancing agricultural production efficiency(Erten et al., 2016; Liu et al., 2019; Lopez-Sanchez et al., 2017).

Polarimetric SAR interferometry (PolInSAR) technology can accurately distinguish various scattering mechanisms and record the vertical structure information through the construction of interferometric coherent scattering models, making it one of the primary technical approaches for obtaining vegetation canopy height(Allies et al., 2021; Cloude and Papathanassiou, 1998). However, due to the rapid growth rate of crops and the relatively low overall vegetation height, traditional interferometry techniques often struggle to provide long spatial baselines with adequate height sensitivity and short time baselines to mitigate time decoherence, leading to inversion failures. Polarimetric SAR (PolSAR) possess unique sensitivity to crop canopy structure and orientation. Additionally, PolSAR can circumvent the temporal baseline and spatial baseline constraints required for interferometric conditions, thus endowing PolSAR with significant potential in the field of crop height estimation. The essence of crop height inversion based on PolSAR lies in establishing a functional relationship between SAR observations and crop biophysical parameters.

The models under non-interference conditions often use microwave radiative transfer theory based on the energy conservation theorem to simulate the backscattering coefficients of the target crop for various vegetation parameters(Karam et al., 1995; Ni et al., 2014). However, the inversion process for the parameters of the model is challenged by the high-dimensional parameter space, frequently resulting in an underdetermined solution. This necessitates extensive Monte Carlo simulations or external measurements to support the inversion process.

To minimize the computational cost required to solve physical models, semi-empirical models establish the functional relationship with backscattering coefficients using empirical coefficients and vegetation parameters. Attema and Ulaby (1978) proposed the Water Cloud Model (WCM), a semi-empirical model for first-order radiative transfer. This model examines the expression for the backscattering coefficient, incorporating target parameters such as soil water content, vegetation water content, and vegetation descriptors. Due to their simplicity and practicality, WCM has been widely used for estimating soil moisture (Chung et al., 2023; Das et al., 2023; Luo et al., 2023; Singh et al., 2023) and inverting vegetation parameters such as Leaf Area Index (Beriaux et al., 2013), aboveground biomass (Baghdadi et al., 2017; Mandal et al., 2019), and vegetation height (Dave et al., 2023; Yang et al., 2022). Improved WCM tailored to specific regions or vegetation types have also been applied for estimating crop height (Chauhan et al., 2019; Mandal

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et al., 2020; Yang et al., 2022). However, WCM does not consider the role of double-bounce scattering, leading to limited applicability for stalk crops where double-bounce scattering is dominant.

The coherent scattering model for vegetation based on analytical wave is closer to reality than the incoherent scattering model. The Random Volume over Ground (RVoG) model currently stands as the most representative model for vegetation height inversion (Treuhaft et al., 1996; Treuhaft and Siqueira, 2000). However, its utilization in the inversion of low and time-varying crop heights is hindered by data acquisition limitations. This is primarily due to the scarcity of interferometric data, which are constrained by spatial and temporal baselines. Ballester-Berman (2020) proposed the RVoG-Backscattering (RVoG-B) model, which is applied to polarimetric SAR (PolSAR) data and is based on the physical framework used in the construction of the RVoG. This framework assumes that the radar signal originates from the scattering mechanism of the crop canopy as well as the double-bounce scattering mechanism between the vegetation and the soil interaction, thus backscattering is treated as a function of vegetation height.

In response to the issue of the existing semi-empirical model, which neglects the double-bounce scattering mechanism based on radiative transfer theory, and considering the growth characteristics of stalk crops under non-interference conditions, the three-component RVoG-B model coherent model is established based on analytical wave theory, accounting for the double-bounce scattering of crop targets. Building upon this, to address the underdetermined solution problem of the physical model, this paper introduces empirical coefficients to develop the RVoG-B three-component semi-empirical model for crop height inversion.

2. Study Data and Methods

2.1 Data and Study Area

The study areas are situated in two adjacent regions in southwestern Ontario, Canada: one to the west of London and the other in proximity to Stratford. Corn in the region was selected for this study. Crop phenology has remained stable over the past five years in both study areas due to consistent crop planting schedules observed throughout the region annually. Specifically, corn is typically sown between May and October annually.

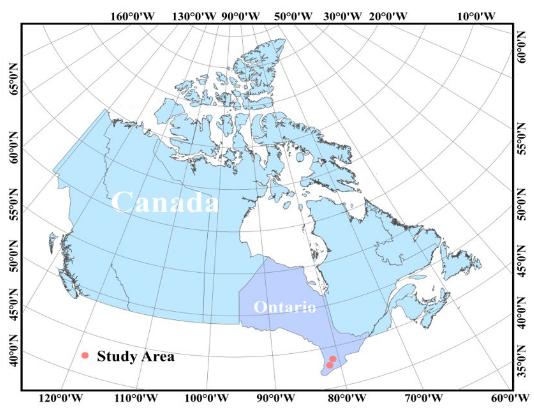


Figure 1. Location of the study area

Prior to extracting PolSAR observations corresponding to the sample points, each RADARSAT-2 image underwent four preprocessing steps: radiometric calibration, formation of the polarimetric coherency matrix, speckle filtering, and geocoding. Specifically, a 9×9 boxcar filter was applied for speckle reduction. Geocoding entailed employing a local Digital Elevation Model (DEM) with a spatial resolution of 30 m to transform the SAR images into the Universal Transverse Mercator (UTM) projected coordinate system (UTM 17N in this study). The coherency matrix images underwent geocoding with a final spatial resolution of 10 m.

In this study, we employed C-band PolSAR data from a set of 24 RADARSAT-2 images, acquired in the years 2013, 2014, 2015, 2018, and 2019. It is noteworthy that the ground-truthing data acquisition campaign was closely coordinated with the acquisition dates of the aforementioned 24 images, with a maximum time difference of no more than 3 days. In this study, a height dataset encompassing the complete growth cycle of corn was assembled, comprising 386 height samples spanning a broad range, with an average height of 177.3cm and individual heights ranging from 3.5cm to 333.75cm. Table 1 provides comprehensive information about the dataset utilized in this study, encompassing the image data, beam model, fieldwork data, and average height values of the samples.

Year	Image Date	Mode	Fieldwork Date	Number of Points	Average height (cm)
2013	20130523	FQ9W	20130524	3	6.2
	20130602	FQ19W	20130604	8	10.0
	20130616	FQ9W	20130616	8	26.5
	20130626	FQ19W	20130624	8	59.6
	20130710	FQ9W	20130710	8	144.2
	20130720	FQ19W	20130720	5	218.6
	20130803	FQ9W	20130803	8	240.7
2014	20140621	FQ15W	20140621	13	17.6
	20140925	FQ15W	20140927	9	295.6
	20141006	FQ9W	20141006	4	281.8
2015	20150623	FQ10W	20150623	24	88.7
	20150810	FQ10W	20150811	6	266.6
	20150903	FQ10W	20150903	6	265.7
	20150913	FQ20W	20150913	6	276.7
2018	20180701	FQ10W	20180704	24	182.1
	20180725	FQ10W	20180725	32	252.8
	20180801	FQ5W	20180802	32	275.2
	20180818	FQ10W	20180818	32	267.8
	20180825	FQ5W	20180825	8	215.0
	20180901	FQ1W	20180901	32	267.0
	20180908	FQ4W	20180911	32	267.2
2019	20190626	FQ11W	20190626	14	19.8
	20190703	FQ5W	20190703	32	43.3
	20190710	FQ1W	20190710	32	68.2

Table 1. Details of RADARSAT-2 images and corresponding ground survey sampling points

Figure 2 illustrates the relationship between backscattering and crop height, indicating that backscattering increases with height up to 120 cm during the pre-growth period of corn, thereby demonstrating a robust correlation between backscattering parameters and corn height. The functional relationship between cross-polarization channel HV and crop height exhibited greater significance compared to the co-polarization channels HH and VV. It is noteworthy that the backscattering coefficients tend to saturate when the corn height reaches 120cm across all three schemes. The backscattering coefficients started to decline beyond 120cm of corn height (late growth stage), and the sensitivity between the backscattering parameters and corn height diminished, particularly when the corn height surpassed 150cm.

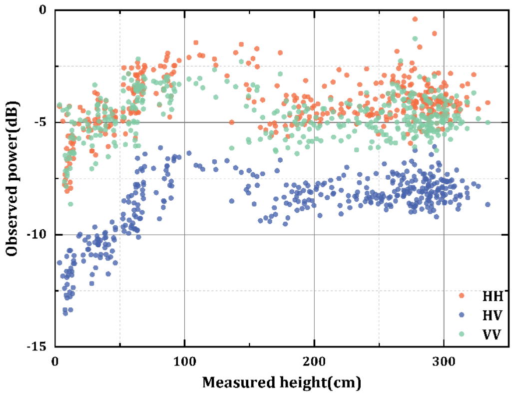


Figure 2. Comparison between backscatter (HH, VV, and HV) and height values for 386 measured sample points

Considering the saturation of backscattering at the late stage of crop growth, this study only discusses the application efficiency of using backscattering parameters to retrieve crop height in the early stage of crop growth (corn height is less than 120cm). In this study, 386 corn sample points were constructed, of which 141 sample points were derived from the early growth data and utilized for model training and subsequent accuracy verification. The study employed the stratified random sampling method, selecting a total of 112 sample points from six equally divided sub-intervals for model training and determination of empirical parameters. The remaining 29 sample points were allocated for verifying the accuracy of crop height inversion.

2.2 RVoG-B Three-component Semi-empirical Model

The RVoG model assumes that the vegetation scene consists of an impenetrable surface layer and a uniformly randomly distributed vegetation layer. The model expresses the complex coherence, denoted as $\gamma(\omega)$, of polarimetric interferometric SAR observations as follows:

$$\gamma(\omega) = e^{i\varphi_0}\frac{\gamma_V(\sigma, h_v) + \mu(\omega)}{1 + \mu(\omega)} \tag{1}$$

where ω = polarimetric channel
φ_0 = surface phase
h_v = vegetation canopy height
σ = extinction coefficient
μ = ground-volume ratios

γ_V is defined as the pure volumetric coherence generated by the vegetation layer. The distribution of scattered energy of electromagnetic waves within the vegetation layer, represented by γ_V, follows an exponential distribution.

$$\gamma_V(\sigma, h_v) = \frac{2\sigma\left(e^{\frac{2\sigma hv}{cos\theta}+ik_z h_v} - 1\right)}{(2\sigma + ik_z cos\theta)\left(e^{\frac{2\sigma hv}{cos\theta}} - 1\right)} \tag{2}$$

$$k_z = \frac{4\pi B_\perp}{\lambda R sin\theta} \tag{3}$$

where k_z = vertical wavenumber
λ = wavelength of the radar waves
$B_\perp$ = length of the perpendicular baseline
R = range or distance
θ = incidence angle

Following the modeling concept of the RVoG model, Ballester-Berman (2020) proposed the RVoG-Backscattering (RVoG-B) model. This framework assumes that the radar signal originates from the scattering mechanism of the crop canopy as well as the double-bounce scattering mechanism between the vegetation and the soil interaction, thus backscattering is treated as a function of vegetation height:

$$P(\omega) = \frac{P_v(\omega)}{2\sigma/\,cos\,\theta}\left(1 - e^{-\frac{2\sigma h_v}{cos\,\theta}}\right) + P_d(\omega) h_v e^{-\frac{2\sigma h_v}{cos\,\theta}} \tag{4}$$

This study assumes that the crop scene is composed of three scattering mechanisms: volume scattering, double-bounce scattering and surface scattering, and constructs the RVoG-B three-component model on the basis of RVoG-B:

$$P(\omega) = \frac{P_v(\omega)}{2\sigma/\,cos\,\theta}\left(1 - e^{-\frac{2\sigma h_v}{cos\,\theta}}\right) + P_d(\omega) h_v e^{-\frac{2\sigma h_v}{cos\,\theta}} + P_s(\omega) e^{-\frac{2\sigma h_v}{cos\,\theta}} \tag{5}$$

where $P(\omega)$ = total backscattering energy
$P_v(\omega)$ = volume backscattering energy
$P_d(\omega)$ = double-bounce backscattering energy
$P_s(\omega)$ = surface backscattering energy

Under the polarimetric channel ω, the model involves a single observed value of backscattering energy $P(\omega)$, yet encompasses 5 unknown parameters: energy from scattering mechanisms $P_v(\omega)$, $P_d(\omega)$, $P_s(\omega)$; extinction coefficient σ; and vegetation height h_v. In order to solve the problem of underdetermination of the model, when only paying attention to the crop height and introducing the empirical coefficient to simplify the physical meaning of the parameters, the equation can be simplified to the RVoG-B three-component semi-empirical model:

$$P(\omega) = a_1(1 - e^{-a_2 h_v}) + a_3 h_v e^{-a_2 h_v} + a_4 e^{-a_2 h_v} \tag{6}$$

where $a_1 = P_v(\omega)/(2\sigma/\,cos\,\theta)$
$a_2 = 2\sigma/\,cos\,\theta$
$a_3 = P_d(\omega)$
$a_4 = P_s(\omega)$

The semi-empirical model expression comprises 4 empirical coefficients and crop height. When employing a single polarimetric SAR observation, a specific number of observed samples suffice to fit the empirical coefficients for crop height inversion. The accuracy of inversion hinges on the quantity and quality of observation samples utilized in the calibration model, along with the polarimetric SAR observations employed.

2.3 Crop Height Inversion Process

According to the RVoG-B three-component semi-empirical model, it enables the estimation of crop height using a single polarimetric channel. The process of crop height inversion based on the RVoG-B three-component semi-empirical model encompasses the following three steps:

1. Model fitting: The least squares fitting algorithm is applied to optimize the empirical parameters using ground height measurements.
2. Build look-up table: Construct a look-up table (LUT), based on crop height, and utilize the determined empirical parameters along with the semi-empirical model to compute the corresponding simulated observations for each crop height in LUT.
3. Height inversion: Crop height is determined based on the minimum difference between simulated and actual observations in the look-up table.

In this study, the diagonal elements of the covariance matrix (C11, C22, and C33) corresponding to the HH, VV, and HV polarimetric channels are utilized as the backscattering parameters and used as the input values for the model. To construct the model and assess the inversion accuracy, 80% of the sample points from the early growth stage were randomly chosen to determine the empirical parameters in the model. The remaining 20% is reserved for verifying the accuracy of crop height inversion.

3. Results

3.1 Model Fitting Results

In order to evaluate and analyse the fitting between the RVoG-B three-component semi-empirical model and backscattering, the parameters of the model were optimized for HH, HV, and VV channels, respectively, by using the early corn growth data training set to determine the empirical parameters of the semi-empirical model. The empirical parameters of the models are determined by the least squares fitting method. The root means square error (RMSE) and correlation coefficient (R) between the estimated backscatter parameters and the observed values are used as evaluation indices to evaluate the effect of model fitting.

Table 2 and Table 3 demonstrates a significant correlation between the RVoG-B three-component semi-empirical model and corn height after determining empirical parameters. The correlation of cross-polarization HV channel (R=0.89) is higher than that of the co-polarization HH channel (R=0.83) and VV channel (R=0.73). The HH and HV channels, which are sensitive to volume scattering and double-bounce scattering, demonstrate higher backscattering accuracy than VV channel, which is sensitive to surface scattering.

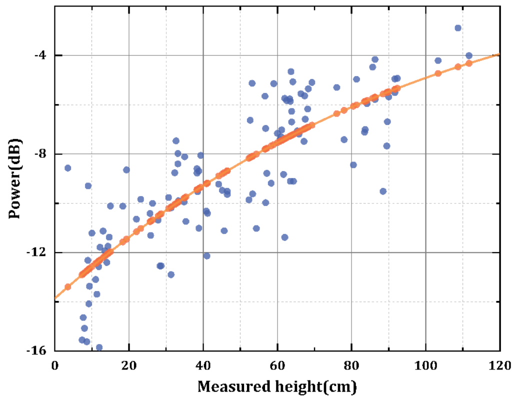
Polarization	a1	a2	a3	a4
HH	-0.0105	0.0139	-0.0581	-13.8620
HV	-5.8932	0.0230	-0.3298	-21.4116
VV	-6.1374	0.0402	-0.2903	-12.6346

Table 2. Model parameters of RVoG-B three-component semi-empirical model

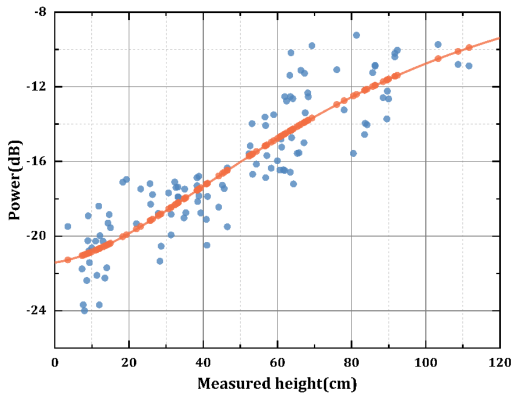
Polarization	RMSE	R
HH	3.21	0.83
HV	3.22	0.89
VV	3.43	0.73

Table 3. Fitting accuracy of RVoG-B three-component semi-empirical model

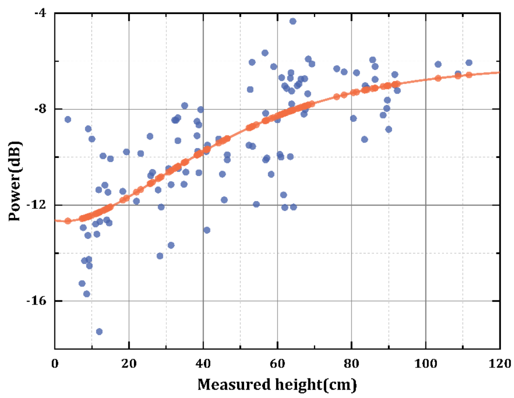
Figure 3 shows the semi-empirical model fitting curve determined by the empirical parameters of least square fitting and the relationship between corn height and backscattering parameter scatter plot. The orange curve represents the trend of the fitting curve, while the blue dots represent the scatter plot between corn height and backscattering parameters. The scatter plots between crop height and backscattering parameters are dense and continuous in HV channel, followed by HH channel, and more dispersed in VV channel. In Figure 3a, the growth rate of backscattering parameters decreases gradually. However, in the HV and VV channels, the RVoG-B semi-empirical model shows that the growth rate of backscattering parameters first increases and then decreases with the increase of crop height (see Figure 3b, c).



(a)



(b)



(c)

Figure 3. RVoG-B three-component semi-empirical model fit curves and scatter plots of corn height versus backscattering parameters: (a) HH (b) HV (c) VV

Based on the fitting results, the RVoG-B three-component semi-empirical model can more clearly describe the relationship between backscattering and crop height in the early growth stage. The model exhibits a distinct changing trend: before reaching the saturation point, the backscattering increases with the increase of crop height. The rate of increase (corresponding to the slope of the fitting curve) initially rises, and when the crop height reaches 40-50 cm, the rate begins to decrease.

3.2 Height Inversion Results

To further verify the ability of the RVoG-B three-component semi-empirical model to retrieve crop height during the early growth stage. The constructed corn sample test set was used in this study, and the semi-empirical model determined by the empirical parameters in Table 3 was used to retrieve the crop height by using LUT. To analyse the accuracy of the inversion results, the inversion accuracy was evaluated by using the RMSE and R between the estimated values of crop height and the measured values on the ground.

As indicated in Table 3, the RVoG-B three-component semi-empirical model exhibits the highest inversion accuracy in the HV channel, with its RMSE=11.66cm and R=0.93. For the HH channel, the corn height retrieval accuracy using the RVoG-B three-component semi-empirical model is RMSE=16.53cm and R=0.86. However, in the VV channel, the RMSE is only 24.51cm with R of 0.70.

Polarization	RVoG-B	
	RMSE (cm)	R
HH	16.53	0.86
HV	11.66	0.93
VV	24.51	0.70

Table 4. RVoG-B three-component semi-empirical model inversion of corn height accuracy

Figure 4 shows the scatter plot between corn height retrieved by the RVoG-B three-component semi-empirical model and the measured value on the ground across different channels. The scatter plot fitting straight line indicates that the RVoG-B three-component semi-empirical model demonstrates excellent inversion results for the HV channel. This can be attributed to the fact that the fitting curve of the RVoG-B three-component semi-empirical model can more accurately descriptive the actual relationship between corn height and backscattering parameters in corn scene for the HV channel. As depicted in Figure 4a, for the HH channel, the RVoG-B three-component semi-empirical model showed overestimation during the early growth stage of corn and the accuracy is slightly lower than that of the HV channel. For the VV channel, the model overestimates corn height when it is less than 70 cm, while it underestimates corn height when it is greater than 70 cm. This instability is mainly attributed to the low sensitivity of the relationship between crop height and VV channel. The RVoG-B three-component semi-empirical model allows single polarimetric channel to retrieve crop height, and the HV and HH channels show excellent crop height retrieval accuracy.

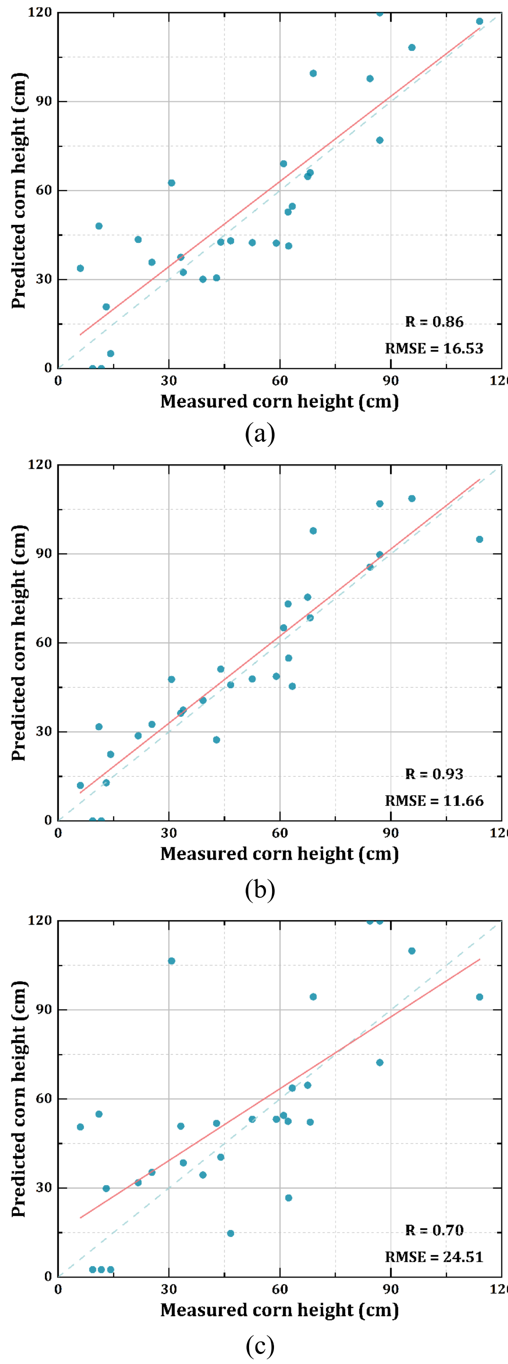


Figure 4. Scatter plots of corn height inversion values versus measured values. (a) HH; (b) HV; (c) VV

4. Conclusions

In this paper, the RVoG-B three-component semi-empirical model for crop height inversion is constructed, which considers the characteristics of double-bounce scattering. The C-band RADARSAT-2 PolSAR data were selected to evaluate the performance of the proposed semi-empirical model in corn height retrieval at the early stage. According to the analysis of the actual relationship between backscattering parameters and crop height fitted by the model, in corn scene, the RVoG-B three-component model can more accurately describe the functional relationship between height and observed values, especially when the polarimetric observations of volume scattering sensitivity and double-bounce scattering sensitivity are used. The crop height inversion results show that when the corn height is retrieved in the early stage of backscattering coefficient saturation (the height is less than 120cm), the HV channel shows greater potential than HH and VV channels. The inversion accuracy of the RVoG-B three-component semi-empirical model is represented by RMSE, ranging between 11.66cm and 24.51cm. Especially when HV channel is used as the observation, the model shows excellent inversion accuracy, and its RMSE reaches 11.66cm. This study demonstrates the potential application of the RVoG-B three-component semi-empirical model for inverting crop height at the early stage dominated by double-bounce scattering.

Acknowledgements

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