WAVELETS BASED OBJECT SURFACE RECONSTRUCTION BY FAST VISION

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ABSTRACT:

An algorithm is presented for the reconstruction of object surfaces with the method of FAST Vision(=FV) using new models derived from wavelets. Firstly, the method of FV will be described briefly. A new, orthogonal and C^1-continuous object grey value model, called 'S-model', was developed from the basic concept of the multiresolution spaces in the theory of wavelets. A high resolution representation of object surface and a *fast* solution of the corresponding normal equations can then be performed. Test results using digitized aerial images with image scale 1:4000 show that FV can perform a fast, highly resolved, reliable and precise determination of object surface in large windows with strict computation of the covariance matrix under the application of the proposed algorithm. The very high resolution of 2 x 2 pixels per height facet (= $0.12 \text{x} 0.12 m^2$ in these tests) is applicable in this algorithm. The precision of the determination of object surface in these tests is ± 0.02-0.06m, i.e. 0.2-0.6 pixel or 0.03-0.1$\%_{oo}$ of flying height above ground, comparing with the control data measured by an operator on the analytical stereo plotter WILD AC3. These figures correspond already to the natural roughness of earth surface and to errors of interior and exterior orientation of the used images.

1. FAST VISION (=FV)

FV is a method to compute simultaneously image matching, digital terrain reconstruction and ortho image generation using digital data from image space and - if available - from object space. It provides very good quality control.

The theory of FV was firstly proposed by Wrobel in 1985 [5,6]. It's basic equation (1) is derived from the inversion of an image formation model:

$$T\{G'(x',y')+v_{G'}(x',y')\}_i = G^0(X^0,Y^0)_i + dG^0(X,Y)_i + \left\{\frac{\partial G^0(X^0,Y^0)_i}{\partial X}\frac{X_i^0-X_0'}{Z_i^0-Z_0'} + \frac{\partial G^0(X^0,Y^0)_i}{\partial Y}\frac{Y_i^0-Y_0'}{Z_i^0-Z_0'}\right\}\cdot dZ(X^0,Y^0)_i \quad (1)$$

where

$\{G'(x',y'), v_{G'}(x',y')\}_i$=observation of the image grey value for the pixel i and its residual;

T=transfer function between image grey value and its corresponding object grey value;

$dG^0(X,Y)_i$=correction of the approximate object grey value $G^0(X^0,Y^0)_i$ that is a function of the corrections of the parameters of the object grey value model;

X_0', Y_0', Z_0'=object coordinate of the projection center of the used image;

X_i^0, Y_i^0, Z_i^0 = approximate object coordinate of the surfel i;

$dZ(X^0,Y^0)_i$= correction of the height for the surfel i, that is a function of the height corrections for the height grid points used in the object height model.

In the past, we used a linear function to approximate the transfer function T, and bilinear approximation functions for the object grey value model and the object height model. One can find detailed descriptions about FV in [2,3,4,5,6] and extended tests in [8].

The well-known *ill-posed problem* in the object surface reconstruction is caused e.g. by a possible deficiency of the necessary image information in the matching window. This problem in FV can be solved by utilizing image and object information. For example, the adaptive regularization [7] uses the smoothness conditions of the geometrical object surface to solve this problem. These conditions are one type of object information.

The bigger the window size, the more image information is available. In this paper we present a wavelets based representation not only to enable the object surface reconstruction in a large matching window, but also to give a good representation of the radiometrical model of the object surface (ortho image). The orthogonal compactly supported wavelets given by Daubechies [1] are applied. We use them to develop an orthogonal and C^1-continuous object grey value model, so that in the normal equations the corresponding submatrix is diagonal, see (6).

2. ORTHOGONAL OBJECT GREY VALUE MODEL: S-MODEL

This new, orthogonal and C^1-continuous object grey value model G(X), called 'S-model', describes a best approximation $A_j\mathbf{G}(X)$ of the ortho image function $\mathbf{G}(X)$ in a certain approximation space V_j, where A_j stands for best approximation in space V_j. The function $A_j\mathbf{G}(X)$ is derived by minimizing a quadratic norm of the residual function ($\mathbf{G}(X)$ - $A_j\mathbf{G}(X)$). From that derivation, we get the S-model G(X) [3]:

$$G(X) = A_j\mathbf{G}(X) = = \sum_k S_k \cdot {}_N\phi\left(\frac{1}{2}\cdot\left[\frac{X-X_1}{\Delta X_G}+1\right]-k+\frac{\tau+J}{2}\right) \quad (2)$$

where

$S_k, \forall k \in \mathbf{N}$ = the parameters of the S-model;

${}_N\phi$ = the scaling function with the support [0, 2N-1];

N = order of the 'Daubechies-wavelets' [1];

X_1 = object coordinate of the first grid point of object grey value;

ΔX_G = the grid size of object grey value;

$\tau = \frac{1}{\sqrt{2}}\sum_{n=0}^{2N-1} h_n \cdot n$;

h_n = low-pass filter coefficients from the Daubechies-wavelets with n = 0 (1) 2N-1;

$h_J = MAX(h_n, \forall n)$, e.g. $J = 1$ for $N = 3,4$.

In case of $X = X_i$, $\forall i \in \mathbf{N}$, i.e. for discrete grid points, equation (2) is equal to

$$G(X_i) = \sqrt{2} \cdot \sum_k S_k \cdot h_{J+i-2k} \quad (3)$$

where:

$$0 \le J + i - 2k \le 2N-1.$$

Here, all of the subscripts i,k with $i,k \in \mathbf{N}$ are used. In these tests we have used N=3, for which the filter coefficients h_0 to h_5 are: 0.33267055, 0.80689151, 0.45987750, -0.13501102, -0.08544127, 0.03522629.

The two-dimensional S-model G(X,Y) is defined by the product of G(X) by G(Y):

$$G(X,Y) = G(X)\ G(Y) = \sum_j\sum_k S_{jk} \cdot \phi\left(\frac{1}{2}\cdot\left[\frac{X-X_1}{\Delta X_G}+1\right]-j+\frac{\tau+J}{2}\right) \cdot \phi\left(\frac{1}{2}\cdot\left[\frac{Y-Y_1}{\Delta Y_G}+1\right]-k+\frac{\tau+J}{2}\right) \quad (4)$$

where:

$$S_{jk} = S_j \cdot S_k,\ \forall j,k \in \mathbf{N}.$$

Equation (4) with $X = X_i, Y = Y_l, \forall i,l \in \mathbf{N}$, is equal to:

$$G(X_i, Y_l) = 2\sum_j\sum_k S_{jk} \cdot h_{J+i-2j} h_{J+l-2k}\ . \quad (5)$$

The corresponding submatrix N_{GG} of the normal equations for the parameters of the object grey value model (=S-model), derived from (1) with (5), becomes much more simpler, e.g. than the band matrix N_{GG} for the (bi-)linear object grey value model:

$$N_{GG} = \lambda \cdot E \quad (6)$$

where:

$$\lambda = 4\sum_{b=1}^{B}\left[\frac{1}{\left(g_1'^0\right)_b}\right]^2;$$

B = number of images, $B \in \mathbf{N}, b \in \mathbf{N}$;

$\left(g_1'^0\right)_b$ = approximate value of the multiplication parameter g_1' in the linear transfer function for the b-th image;

E = unit matrix.

Since in this case the core memory to store N_{GG} becomes very small (only for the element λ), the object surface reconstruction can be performed in large windows. Their size can be further enlarged, if the group adjustment is used.

3. AN EFFECTIVE ALGORITHM

3.1 Basic Idea

The quality of real images, e.g. large scale aerial images, is generally not ideal, i.e. local homogeneous image regions exist very often. In order to keep FV precise using such image data, the window size must be large, so that the probability to find the necessary image information in the window could be higher.

A fast completion of FV needs a fairly good initial DTM (=Digital Terrain Model). In principle, the algorithm of the image pyramid is the most simple way to get a good initial DTM. The matching window in each level of image pyramid should be chosen as large as possible. This gives two advantages: 1) the DTM computed in the upper level from only few windows are prolonged into the neighbouring lower level, so that the total computation time of the object surface reconstruction in a large area becomes shorter; 2) the FV in each level can be more precise and reliable, because strong image textures could exist more likely in a larger window.

Furthermore, the strict adjustment ist not necessary for the computation of FV in the upper levels. Instead of that, the group adjustment is very suitable for the upper levels to rapidly determine the better initial DTM for the lower levels.

In the bottom level, all approximate values of the parameters in FV can be quickly revised in the first iterations by way of the group adjustment and then all parameters can be strictly determined by means of the strict adjustment in the following iterations, if the strict computation of the covariance matrix for all parameters is demanded.

In addition, the *indirect* method of FV and the *parametric cubic convolution function* as a new object height model are used in the following algorithm.

3.2 Algorithm

Because the accuracy of the height points on the border of a window is inferior to the one inside the window, the window size should not be chosen too small. So, a minimal number of facets is required. On the other hand, the window size cannot be too large, because it needs expensive computation costs (huge normal equations and much computation time). Therefore, a suitable computation strategy for a large area, e.g. a *scan-technique*, is demanded from the beginning.

Defining the computation area(s) and the number of levels of the image pyramid in correspondence to the quality of the given coarse DTM.

Low-pass image filtering to produce the image pyramid.

Acquiring better DTM by means of the *from-coarse-to-fine*-algorithm by use of the image pyramid:

- From the top level to the bottom level:
  - Defining each window as large as possible.
  - For the upper levels:
    - Computation with the group adjustment.
  - For the bottom level:
    - Computation with the group adjustment in the first iterations.
    - Computation with the strict adjustment in the last iterations.
    - Output of DTM and ortho image.

Algorithm: *Object surface reconstruction in a large project area by means of the method of FV*

Different scan-techniques are applicable. We use here the simple and practically suitable scan-technique proposed in [2]. In that, a constant number of facets per window is used in every level. The overlap between two neighbouring scan-windows is defined such, that the computed heights of a certain number of facet points on the border of scan-window are not accepted for the final DTM. The mean value of computed heights on a point, that lies in two neighbouring scan-windows, is registered in the DTM.

In the new algorithm, the DTM and ortho image in a large project area are determined by moving scan-windows with constant size. Firstly, the computation areas are defined as parts of the total project area and the appropriate number of levels of the image pyramid is chosen. The image data in the upper levels are determined by means of low-pass filtering.

The precision and other characteristics of the object surface reconstruction by FV under application of this algorithm were tested and analyzed in [3] using large scale aerial images. We show a summary as follows.

4. EXPERIMENTAL RESULTS

The selected test area (Fig. 1) is a rural region in Walddorf-Häslach in the southwest of Germany, where three test windows are chosen: window A with relatively good texture, window B with intermediate texture in a slope along a freeway, and window C with weak texture. Thereby, object surface reconstruction in different types of windows can be tested. The height differences in the windows A,C and B are 0.8m and 2.5m, respectively.

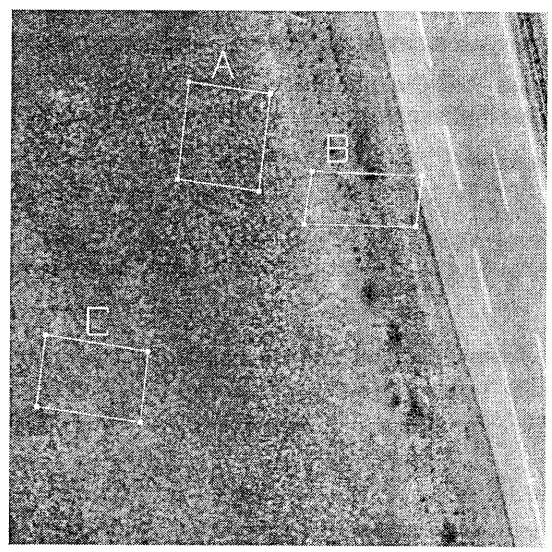

Fig. 1: *Image of the test area including the three test windows A,B,C (image size 800 x 800 pixels, pixel size 15 x 15 μm^2)*

Comparing with other aerial images (small scale, different regions), the texture in this test area is very weak. Therefore, this test area exhibits a genuine touchstone for the FV using aerial images.

The aerial photos were taken with the scale 1:4000 using the camera Zeiss RMK A 15/23 (focal length = 15cm, photo format = 23 x 23 cm^2). From them, four photos that belong to two crossing flying lines, are chosen. The overlap between two neighbouring photos in a flying line is approx. 60%. These four photos are digitized using the photo scanner PS1 with pixel size 15 x 15 μm^2 and 8 bits per pixel (i.e. 256 grey value steps).

The algorithm of the image pyramid is used to determine the initial DTM in all tests. A horizontal plane is utilized as the initial height surface in the top level. 4 and 5 levels of image pyramid are employed for the windows A,C and B, respectively. With that, the precision of initial DTM is $2\%_{o}$H(=1.2m) and $3\%_{o}$H (=1.8m) respectively, where the notion H means the flying height above ground and will be used in the following text. That also corresponds to the precision of x-parallax about 1.5 pixels and 1.1 pixels in the top level.

DTMs with the grid size 0.5 x 0.5 m^2 in these three windows were measured by an operator on the analytical stereo plotter WILD AC3 to compare with the computed DTM by FV. The measuring precisions (Tab. 1) show the different quality of texture in these windows: A and B are approximately the same, C is inferior.

window	k	n	$\hat{\sigma}_{0,Z,OP}$ [m]	$\bar{\hat{\sigma}}_{\bar{Z},OP}$ [m]	$\hat{\sigma}_{\bar{Z},OP,max}$ [m]
A	320	1943	0.07	0.03	0.08
B	209	936	0.08	0.04	0.11
C	300	920	0.14	0.08	0.16

Tab. 1: Statistic data of the height measurements in the windows A,B,C with the grid size 0.5x0.5m^2 by an operator on the analytical stereo plotter WILD AC3.

k = number of Z-points; n = number of Z-measurements;
$\hat{\sigma}_{0,Z,OP}$ = the global precision of each single Z-measurement;
$\bar{\hat{\sigma}}_{\bar{Z},OP}$, $\hat{\sigma}_{\bar{Z},OP,max}$ = the mean and maximal value of the standard deviations of the mean Z-values.

The following data will be given in the following tables to judge the precision of the computed DTM by FV:

$\hat{\sigma}_0$ = the standard deviation of unit weight (grey value);

$\bar{\hat{\sigma}}_{Z,FS}$, $\hat{\sigma}_{Z,FS,max}$ = the mean and maximum of the standard deviations of the Z-values, determined in the computation of FV;

s_{FS} / s_{OP} = the standard deviation *a posteriori* of the computed Z-value $(Z_{FS})_i$ by FV and of the mean $(\bar{Z}_{OP})_i$ of the height observations measured by an operator on the grid point i, i = 1 (1) k (both are derived from the measured DTM by operator);

$|dZ_b|_{,max}$ = the maximum of the absolute values of the resolved height differences $(dZ_b)_i$, i = 1 (1) k;

$\Delta Z \pm s_{\Delta Z}$ = the constant height difference between both DTM $(Z_{FS})_i$ and $(\bar{Z}_{OP})_i$, i = 1 (1) k, and it's standard deviation,

where $(Z_{FS})_i$ - $(\bar{Z}_{OP})_i$ = $(dZ_b)_i$ + ΔZ. One can find the related detailed descriptions in [3].

Parts of the test results for the window C will be analyzed briefly as follows. They are in good agreement with the other ones for the window C and the ones for the windows A and B.

Tab. 2 shows the test results using 2 images, where 2x2 pixels per G-facet and 4x4 pixels per Z-facet are used, denoted by

$$P : G : Z = 1 : 2^2 : 4^2.$$

One sees clearly that all computations converge in 2 or 3 iterations. $\hat{\sigma}_0$ becomes larger from the upper level to the lower one. That is caused obviously by the low-pass image filtering from the lower levels to the upper ones, where image noise is damped down.

The standard deviations of heights, that are determined by FV, become smaller from the upper level to the lower one, i.e. from coarse resolution to fine one. The standard deviations a posteriori s_{FS} of the computed Z-values by FV in the 1st level are less than or equal to 3 cm (=0.05$\%_{o}$H) that corresponds to 0.3 pixel in the image space. Also $\Delta Z \sim 0$, i.e. there exists no offset between both DTM $(Z_{FS})_i$ and $(\bar{Z}_{OP})_i$. The value $|dZ_b|_{,max}$ is equal to 13 cm in the 1st level.

Furthermore, 82.3% of the resolved height differences are located in the interval $\pm$6cm (=0.1$\%_{o}$H), i.e. 0.6 pixel.

Tab. 3 shows the test results using 4 images. Comparing with the ones using 2 images (Tab. 2), the precision of the object surface reconstruction using 4 images is better than the one using 2 images with respect to $\hat{\sigma}_0$ and s_{FS}.

All standard deviations a posteriori, s_{FS}, of the computed heights by FV in the 1st level are smaller than 3cm, i.e. 0.05$\%_{o}$H or 0.3 pixel in the image space, where the constant height difference ΔZ is not significant, i.e. $\Delta Z \sim 0$.

Tab. 4 shows the test results using 4 images and the very high resolution of 2x2 pixel per Z-facet and with G-facet = Z-facet, denoted by

$$P : G : Z = 1 : 2^2 : 2^2.$$

This is the maximum resolution applicable for FV using the S-model as the object grey value model. In that case, all computations converge in 2 or 3 iterations. As before (Tab. 2 and 3), $\hat{\sigma}_0$ becomes larger from the upper level to the lower one. The standard deviations a posteriori s_{FS} of the computed heights by FV in the 1st level are 3-4cm (=0.05-0.07$\%_{o}$H), i.e. 0.3-0.4 pixel in the image space. So, the precision of FV at maximum resolution is only slightly less than the one with the lower resolution

level of image pyramid		number of Itera-tions	$\hat{\sigma}_0$ [grey value]	$\bar{\hat{\sigma}}_{Z,FS}$ [m]	$\hat{\sigma}_{Z,FS,max}$ [m]	s_{FS} / s_{OP} [m]	$\lvert dZ_b \rvert_{,max}$ [m]	$\Delta Z \pm s_{\Delta Z}$ [m]
4		2	3.8	0.25	0.38	0.22 / 0.07	0.45	-0.04 ± 0.04
3		2	5.3	0.11	0.23	0.17 / 0.12	0.45	-0.03 ± 0.02
2		2	7.5	0.07	0.15	0.11 / 0.12	0.42	-0.02 ± 0.01
1	1.1	3	9.1	0.04	0.09	0.02 / 0.04	0.13	-0.00 ± 0.00
	1.2	3	10.3	0.05	0.10	0.03 / 0.04	0.13	-0.00 ± 0.00

Tab. 2: Test results with the method of FV **using 2 images, window C (weak texture)**

Number of pixels per facet : P : G : Z = $1 : 2^2 : 4^2$

Facet size in 1. level of image pyramid : Δ X(P) : Δ X(G) : Δ X(Z) = 0.0625m : 0.125m : 0.25m

level of image pyramid		number of Itera-tions	$\hat{\sigma}_0$ [grey value]	$\bar{\hat{\sigma}}_{Z,FS}$ [m]	$\hat{\sigma}_{Z,FS,max}$ [m]	s_{FS} / s_{OP} [m]	$\lvert dZ_b \rvert_{,max}$ [m]	$\Delta Z \pm s_{\Delta Z}$ [m]
4		2	3.7	0.21	0.35	0.21 / 0.08	0.45	-0.04 ± 0.04
3		2	4.9	0.09	0.19	0.16 / 0.14	0.45	-0.03 ± 0.02
2		2	6.6	0.06	0.12	0.10 / 0.13	0.44	-0.03 ± 0.01
1	1.1	3	8.8	0.04	0.09	0.02 / 0.04	0.18	0.01 ± 0.00
	1.2	3	9.7	0.04	0.09	0.03 / 0.05	0.18	-0.00 ± 0.00

Tab. 3: Test results with the method of FV **using 4 images, window C (weak texture)**

Number of pixels per facet : P : G : Z = $1 : 2^2 : 4^2$

Facet size in 1. level of image pyramid : Δ X(P) : Δ X(G) : Δ X(Z) = 0.0625m : 0.125m : 0.25m

level of image pyramid		number of Itera-tions	$\hat{\sigma}_0$ [grey value]	$\bar{\hat{\sigma}}_{Z,FS}$ [m]	$\hat{\sigma}_{Z,FS,max}$ [m]	s_{FS} / s_{OP} [m]	$\lvert dZ_b \rvert_{,max}$ [m]	$\Delta Z \pm s_{\Delta Z}$ [m]
4		2	3.8	0.52	1.25	0.11 / 0.02	0.32	-0.02 ± 0.01
3		2	4.5	0.17	0.66	0.08 / 0.04	0.25	0.00 ± 0.01
2		2	5.9	0.11	0.46	0.06 / 0.04	0.24	-0.02 ± 0.01
1	1.1	3	8.5	0.09	0.41	0.04 / 0.04	0.13	-0.00 ± 0.01
	1.2	2	10.1	0.09	0.31	0.04 / 0.04	0.12	-0.02 ± 0.01
	1.3	2	9.2	0.08	0.28	0.03 / 0.03	0.11	0.01 ± 0.01
	1.4	3	10.3	0.09	0.31	0.03 / 0.03	0.13	-0.00 ± 0.01

level of image pyramid		RMS(dZ) [m]	$\lvert dZ \rvert_{,max}$ [m]
4		0.11	0.34
3		0.09	0.25
2		0.07	0.26
1	1.1	0.05	0.13
	1.2	0.06	0.14
	1.3	0.05	0.12
	1.4	0.04	0.12

Tab. 4: Test results with the method of FV **using 4 images, window C (weak texture) and a high resolution**

Number of pixels per facet : P : G : Z = $1 : 2^2 : 2^2$

Facet size in 1. level of image pyramid : Δ X(P) : Δ X(G) : Δ X(Z) = 0.0625m : 0.125m : 0.125m

(Tab. 2 and 3). They are less than the means $\bar{\hat{\sigma}}_{Z,FS}$ (=8-9cm) of the standard deviations of the computed heights by FV. This indicates that the heights can be determined more precisively than their precision indicators $\hat{\sigma}_{Z,FS}$. It is an expected effect of the *bridging function* performed by the *regularization* used.

In these tests, $\Delta Z \sim 0$, i.e. the constant height difference ΔZ is not significant. The means of quadratic height difference dZ, i.e. RMS(dZ), in the 1st level are 4-6cm (=0.07-0.1$^{0}\!/_{00}$H) or 0.4-0.6 pixel in the image space.

In addition, such precisions reach already the limit that is determined by the following two factors: 1) the accuracy of the interior and exterior orientation of the images used lies already at 0.2-0.3 pixel; 2) the natural roughness of earth surface in this test area is surely about the same as the reached precision, that is less than 10cm.

Altogether, the test results show that FV is capable of a precise object surface reconstruction using large scale aerial images. Furthermore, the proposed algorithm using new models derived from wavelets enables an object surface reconstruction using the very high resolution of 2x2 pixels per Z-facet (=0.12x0.12m^2). That is much finer than the one that has been obtained with any other available method known so far.

5. CONCLUSIONS

Facets stereo vision, abbreviated with 'FAST Vision' or 'FV', is a method for the object surface reconstruction using digital images. The basic equations of FV are founded on the inceptive draft of *image inversion* using object space models [5,6]. In this paper, the new, orthogonal and C^1-continuous object grey value model, called 'S-model', is presented. It was derived from the basic concept of multiresolution spaces in the theory of wavelets. The orthogonal compactly supported wavelets given by Daubechies [1] are applied (S-model). Using the S-model, the very high resolution of 2x2 pixels per Z-facet (= 0.12x0.12m^2 in the presented tests) is applicable in FV. It can be carried out a *fast*, high resolution, reliable and precise determination of the geometrical and radiome-trical object surface (=DTM and the ortho image) in large windows. The test results using the aerial images with image scale 1:4000 show that the reached precision of the object surface reconstruction by FV is 0.2-0.6 pixel, comparing with the measured DTM by an operator on the analytical stereo plotter WILD AC3. These figures already reach the limits under the consideration of the accuracy of the orientation of the images used and the natural roughness of earth surface.

Examining the present suppositions and conditions of FV, there exist still some topics for further improvements, e.g. processing or modeling breaking lines on the object surface, an optimal regularization, a better reflection model, geometrical and radiometrical calibration of the used photo scanner or CCD-camera, ... etc.

In addition, integration of different informations into FV is possible, because the FV can be regarded as a conceptual synthesis and a good recipe for *Digital Photogrammetry*. This is a remarkable potential of FV. At present, one takes only geometrical and radiometrical information of the object surface into account. The research works about the introduction of semantic information of the object surface into FV for object surface reconstruction are not yet done until now.

Furthermore, the reconstruction of the earth surface is required for the topographic cartography. The methods or algorithms to extract the desired earth surface from the total reconstructed object surface inclusive the surfaces of, e.g., houses and vegetations should be further developed and proposed.

Finally, the S-model proposed in this paper, can be further improved or even new and more suitable models for FV can be presented, if better and more effective wavelets could be developed in the coming years.

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