Flooding Water Depth Estimation With High-Resolution SAR

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Abstract—The retrieval of flooding levels with high-resolution (HR) synthetic aperture radar (SAR) images is presented in this paper. A new framework is proposed. It is based on the inversion of theoretical scattering models initially developed for nonflooded urban areas and here adapted to the flooding case. Starting from the theory, two possible retrieval approaches have been developed and are the main topic of this paper: two possible retrieval approaches have been developed and are the main topic of this paper: the local Single Image Objects Aware (SIObA) and the global Two Image Area Aware (TIArA). These two approaches are conceived to be applicable under different working conditions and consequently holding different properties and reliability. For each of them, a different algorithm is derived and tested, and the retrieval results are validated on a meaningful data set of HR TerraSAR-X images relevant to the Gloucestershire (U.K.) flooding that occurred in year 2007.

Index Terms—Electromagnetic modeling, feature extraction, floods, inverse problems, Synthetic aperture radar (SAR).

I. INTRODUCTION

CLIMATE change is clearly playing an important role in the current increase in flooding occurrence: That in the U.K. in 2007 and in 2014 or in Pakistan in 2010 are only some of the most devastating water disasters that happened recently. The loss in lives, properties, agricultural harvests, and infrastructures is anytime evaluated in terms of millions of dollars [1], [2], with peaks of billions per single event [1], thus justifying the research of efficient *real-time* technical solutions to synoptically monitor the increase of river/ocean levels and prevent or mitigate the event of flooding.

Many are the initiatives in this sense that are trying to respond to the general directives on this subject: For instance, the European Union level, clear statements are made in the Floods Directive [3] about the need, in each Member State, of undertaking preliminary flood risk assessment and preparing flood hazard and risk maps at appropriate scales for all areas likely to be affected. All these actions are needed to better face future risks. Within this respect, numbers are absolutely impressive: For instance, in the sole England territory, it has been estimated that around 5.2 million properties are at risk

of flooding and more than 5 million people live or work in buildings at risk of flooding [4].

With the Floods Directive entered into force, clear deadlines have been set out to guarantee an effective implementation. In particular, flood hazard and flood risk maps were to be developed by the end of 2013. These flood risk maps, based on the risk functions, allow delimiting and classifying the different areas according to the hazard (the probability associated to the flood event) and the vulnerability (characteristics related to the potential damages of the flood-prone areas) associated to the flood [5]. In addition, a flood risk management plan must be drawn up for risk areas by the end of 2015 for each Member State of the European Union [6]. This will include measures of prevention, protection, and preparedness. An Atlas is now available on best flood mapping practices [7], and the information there required is [3], [6] as follows: flood extent, water depths or water level, flow velocity, or the relevant water flow. Obviously, all those parameters are crucial in emergency situations, and monitoring them (in space and time domain) during an event is much more useful (in any sense) for preparedness compared to any post-flooding damage assessment. The need of a reliable tool where all that information is provided in real time becomes then clear.

So far, aerial photography has been considered the most reliable remote sensing source for flood monitoring, and consequently, it has been more extensively used than radar images [8]; nevertheless, the high costs (and sometime risks) associated with airborne acquisitions (in crisis conditions) and the capability of (spaceborne) synthetic aperture radars (SARs) to get images independently from weather conditions and daytime make SAR to be regarded as a valid alternative.

Today, the availability of spaceborne SAR sensors is (potentially) supporting the flood monitoring and management. In particular, the available constellations of SAR sensors almost meet the standard temporal resolution requirement for this kind of disaster monitoring (on the order of 3–4 h). As regards the kind of sensor to use, the issue of urgency drives the choice as only a SAR can guarantee cloud- and daylight-independent acquisitions. COSMO-SkyMed, for example, is a four-satellite constellation equipped with SAR sensors that are able to satisfy each User Request¹ within 72 h in normal conditions (routine mode), 36 h in crisis mode, and 18 h during emergencies (urgent mode) [9]. Moreover, other SAR sensors are in orbit such as the German TerraSAR-X/Tandem-X [10], the Canadian RADARSAT-2 [11], and the European Union's Sentinel-1 [12]. Many others are currently under design and

¹Ability to deliver the image product required by an End User in a timely manner [9]

likely to be launched soon or in the next couple of years (NovaSAR-S, SAOCOM, and ALOS-2). This scenario is going to be crucial to support SAR data applications, with a coverage capability never reached before. The joint use of these sensors will drastically decrease the revisit time even if the need for an appropriate fusion framework will be required.

SAR is very capable in the 2-D monitoring of flooding spatial extent owing to the very low radar return relevant to flooded areas causing dark appearances in SAR images. Within this framework, most of the studies in the literature are about flood detection [13], [15], and near real-time solutions are also suggested [16]. Relying on [17], the information on double scattering between the ground surface and the building wall when the surface is flooded is exploited in [18] to increase the effectiveness at detecting urban flooding in layover regions. Measurements of double scattering radar cross sections (RCSs) are compared to the predictions from an electromagnetic scattering model for the cases of a single image with flooding and a change detection scenario; finally, the results from [18] are included in the flood-map algorithm presented in [16] by the same authors to improve the overall detection performance. In [19], a flood map is retrieved by using a three-step algorithm. The authors combine a classical backscatter thresholding with a region growing together with a change detection approach. The change detection reduces the false alarm probability due to shadow areas, which appear as dark as the flooded pixel, by employing a couple of SAR images (one flooded and one unflooded). Only pixels that significantly change their backscatter values in the two images are kept in the flood extent map [19].

In [20], a method is introduced to combine pre- and post-flood images, thus obtaining a color composite image able to identify the flooded areas; the aim is obtained by introducing a novel preprocessing phase (cross-calibration/normalization) which enhances the numerical comparison of different images and makes the discrimination between flooded and unflooded areas easier.

Conversely, a 3-D characterization of floods (including the vertical scale, i.e., the water height meant as variable quantity on the sensed area) is still poorly addressed in the literature both for optical and SAR sensors: In [21], some results are obtained by employing a digital elevation model (DEM). In case of aerial photographs, the vertical root-mean-squared error (RMSE) of ~ 20 cm [22] can be achieved but at the cost of an expensive and complex methodology based on extensive fieldwork, hydraulic knowledge, and aerial photography interpretation skills. In [23], a 2-D flood inundation model (LISFLOOD-FP) is calibrated and evaluated by using DEM data together with three aerial photographs acquired in three different days during the 2007 Tewkesbury flooding. The results show the RMSE between 49 and 55 cm in the best case [23]. In a similar way, SAR has been used in conjunction with high-precision photogrammetric data to estimate an uncertainty between the maximum and the minimum water depth of ~ 30 cm on average [24] in the presence of hydraulically sensitive zones. The same method applied to a lower magnitude flood event resulted in a worse average uncertainty of 54 cm [24]. In [25], remote sensing data sets, both from optical and SAR (TerraSAR-X, RADARSAT-1, and ENVISAT) images, are used in conjunction with LiDAR data to retrieve the inundation level that occurred during the 2007 Tewkesbury flooding. Results are validated

against with the LISFLOOD-FP simulations introduced in [23] and show better performances for images with higher spatial resolution [25].

A different local-based approach for water level estimation based on the availability of just one SAR post-event image was introduced in [17]. The overall complete framework behind that approach plus an additional general method are presented, discussed, and tested in the next sections.

The framework presented in this paper has additional benefits. As anticipated, the information required is provided with the minimum number of SAR data sets: one post-event SAR image for water extension and level and one more SAR image for each new estimation of flow rate. This allows for fast monitoring since the acquisition time of images is reduced to the minimum. In terms of user needs, as anticipated, two further important requirements and relevant precisions should be considered: the water level with centimetric error and the flow velocity with at least hourly rate. The first requirement is addressed here through the inversion of scattering models considering all relevant radar and scene parameters. The adoption of an electromagnetic model in the detection procedure allows for an error in the water level estimation independent from the image spatial resolution, somehow limited to the employed carrier wavelength, thus meaning that, in principle, centimetric errors can be achieved.

This paper is organized as follows. In Section II, the underlying electromagnetic models are presented. Their inversion forms the fundamentals of the *Single Image Objects Aware* (SIObA) and the *Two Image Area Aware* (TIArA) approaches for flood monitoring are described in Section III. In Section IV, both approaches are tested and validated on the case study given by the Gloucestershire flooding in 2007, and results are discussed. Finally, conclusions are drawn.

II. ELECTROMAGNETIC BACKGROUND

The flooding scenario is often a really complex phenomenon, and many aspects have to be taken in account: dielectric constants of the water and wet materials, heterogeneity of the water surface and of the soil, ground swell and ripples, and debris brought from the flow. In order to study such a scenario, it is necessary to introduce a canonical problem.

In the following, we consider a canonical flooding scenario, starting from a previous canonical model introduced for isolated buildings in unflooded areas in [26] and [27]. We initially refer to a scene composed by one isolated building on a rough terrain. The building is modeled as a parallelepiped, with smooth vertical walls (without balconies or windows) and a flat roof. Conversely, the terrain is modeled, for the sake of simplicity, via a Gaussian stochastic process with a Gaussian autocorrelation function: Note that more involved stochastic processes can be easily considered in the following derivation [28].

In the aforementioned hypotheses, in the unflooded case, it is possible to introduce and evaluate the different contributions of the electromagnetic field backscattered from the scene and describe how they are mapped onto a SAR image [29]; in addition, some algorithms have been proposed to retrieve the geometric parameters of the scene, such as the building height, by simply measuring some geometric quantities on the SAR

image, like the number of pixels in the range direction relevant to the layover or shadow areas [30], [31]. However, this kind of retrieval procedure intrinsically leads to measurement errors in the order of the range resolution cell [27]. Better results are obtained if the feature extraction method is based on the evaluation of radiometric quantities relevant to the backscattered field, like the RCS [27]: in this case, at least in principle, the measurement errors are in the order of the electromagnetic wavelength λ [27]. The main results of the aforementioned approach are here recalled because they are used for isolated buildings in unflooded areas.

In the high frequency regime, where the dimensions of reflecting objects are much larger than the electromagnetic wavelength, the backscattered electromagnetic field is evaluable in the phasor domain in closed form by using the Kirchhoff approach within the physical optics (PO) or geometrical optics (GO) solutions according to the ground roughness. However, buildings on a rough terrain violate the use of these solutions directly for the entire composite structure. These solutions can be, however, somehow restated if multiple bounce decomposition is performed [26], [29]. In this case, the link between the building height and the RCS of single, double, or triple contributions [26] becomes evident: At each bounce, GO or PO can be employed, depending again on the wall or terrain roughness. Since triple contributions are often mixed with contributions from the roof and the wall and are not easily detectable on a SAR image, we will limit our analysis to the single and double bounce mechanisms as in [27]. Knowing the geometry of the building, the different scattering contributions expected on a SAR image can be identified and evaluated, and the double reflection contribution and the single scattering can be isolated. According to Franceschetti *et al.* [26] and Guida *et al.* [27] and scanning the SAR image, from near to far (slant) range at any constant azimuth, we expect to find, for each isolated building, first the layover area (single scattering mechanism from the roof and lateral wall), followed by the double reflection contribution (located in the vertex created by the basis of the wall and the rough terrain), and, finally, the scattering from the roof, the triple scattering, and the shadow area [29]. All the double-scattered rays have the same time delay and they sum in phase; for this reason, their contribution appears much brighter than any other and is usually preferred for the height extraction [27].

For the sake of completeness, we here report the analytical expression provided in [26] which can be used for the building height retrieval. Considering the contribution from single scattering, it is possible to link the RCS of the layover area to the building height through the following equation:

$$\sigma^0 = f(\mathbf{g}; h) \quad (1)$$

where σ^0 is the RCS and $f(\mathbf{g}; h)$ is a function of the building height h and a known parameter vector $\mathbf{g}$ that depends on the following: the building length (l), the complex dielectric constant of the building wall (ε_b), the radar signal wavenumber ($k = (2\pi/\lambda)$), the angle between the sensor line of flight and the projection of the building wall to the ground (φ), and the SAR look angle (ϑ). In this model, the building wall surface is smooth, and therefore, the scattered field according to the GO approach is a wave plane propagating along the specular di-

rection giving a null backscattering contribution apart from the case of $\vartheta = (\pi/2)$ and $\varphi = 0$ [26]. In the PO approximation, instead, the function $f(\mathbf{g}; h)$ is given by the following:

$$f(\mathbf{g}; h) = \frac{|S_{pq}|^2 \sin^2(kh \cos \vartheta) \sin^2(kl \sin \varphi \sin \vartheta)}{4\pi k^2 \cos^2 \vartheta \sin^2 \vartheta \sin^2 \varphi} \quad (2)$$

where S_{pq} is the generic element of the scattering matrix with p and q standing for horizontal, H , or vertical, V , polarization, respectively [26]; S_{pq} depends on ε_b , φ , and ϑ ; and $k = (2\pi/\lambda)$.

In the case of the double reflection contribution, (1) can be factorized as the product of two factors, and the equation can be rewritten as

$$\sigma^0 = h \cdot f(\mathbf{p}) \quad (3)$$

where $f(\mathbf{p})$ is a function of a known parameter vector $\mathbf{p}$ that depends on the following: l , ε_b , k , φ , ϑ , the standard deviation (σ), and the correlation length (L) of the stochastic process representing the ground surface and the complex dielectric constant of the soil surface (ε_s).

The function $f(\mathbf{p})$ is given by [27]

$$f(\mathbf{p}) = |S_{pq}|^2 l \tan \vartheta \cos \varphi \exp(-4k^2 \sigma^2 \cos^2 \vartheta) \times \sum_{m=1}^{\infty} \frac{(2k\sigma \cos \vartheta)^{2m}}{m!} \frac{k^2 L^2}{4m} \exp\left[-\frac{(2kL \sin \varphi \sin \vartheta)^2}{4m}\right] \quad (4)$$

for the GO-PO approach; alternatively

$$f(\mathbf{p}) = \frac{|S_{pq}|^2 l \tan \vartheta \cos \varphi (1 + \tan^2 \vartheta \sin^2 \varphi) \exp\left[-\frac{\tan^2 \vartheta \sin^2 \varphi}{2\sigma^2 (2/L^2)}\right]}{8\pi^2 \sigma^2 (2/L^2) \cos^2 \vartheta} \quad (5)$$

for the GO-GO solution (meaning that both first and second bounces are evaluated via GO solutions). In (4) and (5), S_{pq} depends on ε_b , ε_s , φ , ϑ , and k . The GO-PO approach (GO solution employed for the wall and PO solution employed for the terrain scattering) can be employed if the product $k\sigma \ll 1$; vice versa, GO-GO can be used if $k\sigma \gg 1$ [26].

Equations (1)–(5) allow estimating the building height as detailed in [26] and [27] and can be conveniently applied for the case of unflooded areas; however, since the double reflection is the strongest amplitude contribution among all the scattering contributions and therefore the easiest detectable [27], only (3)–(5) relevant to the double reflection contribution are considered in the following analysis. Here, we reconsider the simple retrieval approach in a novel way to account for the presence of water; this is done to estimate the flood level itself. When a flood occurs, several changes to the aforementioned reported formulation must be considered. On the one hand, the portion of the building contributing to the overall scattering mechanism decreases, and consequently, also the building-ground dihedral changes its geometric properties, bringing to a displacement and a reduced brightness of the double reflection contribution; from the other hand, the permittivity of water is much greater than that of dry soil, thus changing the dielectric properties of the building-ground dihedral (now a “building-water” dihedral) and leading to a brighter double reflection contribution [32]. In addition, the correlation length of the random process describing the ground would increase while the standard deviation would decrease (as the soil is replaced by water),

Fig. 1. Displacement (ΔR) of the double reflection line in the flood scenario.

thus resulting in a darker ground onto SAR images. As a consequence, the buildings at the boundary of the flooded zone, where the flood level is lower, should present a brighter double reflection contribution. Moreover, it is worth to mention that the difference between the pre- and post-flood SAR image intensities becomes more remarkable if the acquisition is performed in HH polarization [33].

Let us make the following assumptions: 1) the pre- and post-images are acquired with the same radar and orbit parameters; 2) the building does not change, neither geometrically (i.e., collapse or addition of new floors) nor electromagnetically (i.e., the dielectric constants stay the same), between the two acquisitions; and 3) the water is considered infinitely deep so that no multiple bounces can arise from under the water's surface. With these hypotheses, (4) and (5) can be reformulated for the flooding case as follows:

$$f(\mathbf{p}) = |S_{pqw}|^2 l \tan \vartheta \cos \varphi \exp(-4k^2 \sigma_w^2 \cos^2 \vartheta) \times \sum_{m=1}^{\infty} \frac{(2k\sigma_w \cos \vartheta)^{2m}}{m!} \frac{k^2 L_w^2}{4m} \exp\left[-\frac{(2kL_w \sin \varphi \sin \vartheta)^2}{4m}\right] \quad (6)$$

for the GO-PO approach; alternatively

$$f(\mathbf{p}) = \frac{|S_{pqw}|^2 l \tan \vartheta \cos \varphi (1 + \tan^2 \vartheta \sin^2 \varphi) \exp\left[-\frac{\tan^2 \vartheta \sin^2 \varphi}{2\sigma_w^2 (2/L_w^2)}\right]}{8\pi^2 \sigma_w^2 (2/L_w^2) \cos^2 \vartheta} \quad (7)$$

for the GO-GO solution. In (6) and (7), $|S_{pqw}|$ is the module of the scattering matrix in the presence of water, while σ_w and L_w are the standard deviation and the correlation length of the stochastic process representing the water surface.

In addition, the position of the double reflection contribution of the building in the SAR image of the flooded scenario presents a shift toward the near range compared to the ordinary case (the same building in the unflooded conditions), given by

$$r_f = r_{uf} - \Delta R \quad (8)$$

where r_f and r_{uf} are the range position of the double reflection contribution in the flooded and unflooded scenarios, respectively, and ΔR is the displacement in range occurring for the presence of water. The displacement is evaluated according to (see Fig. 1)

$$\Delta R = h_w \cos \vartheta \quad (9)$$

where h_w is the water level of the flooding.

In the next section, the direct model here presented for the flooded case is inverted, and two novel approaches for the flooding level estimation are introduced and described.

III. METHODOLOGY

The scattering models in Section II can be inverted to retrieve the water level from SAR images of urban areas during a flooding event. The main advantage of those models is represented by their closed-form equations which are easily invertible so that information about different variables, such as the water level, can be estimated. On the other side, the assumptions made to derive those models entail a high *a priori* knowledge of the scene, together with the radar parameters.

In particular, a proper inversion of the scattering models brings two novel techniques for the flood level estimation which are here presented: the SIObA and the TIARa.

A. Single Image Object Aware

The SIObA is a local-based approach relying on just one SAR image acquired during the event or post-event (*Single Image*) and allowing the evaluation of the water level in the proximity of a selected local building target if the *a priori* knowledge of the target ground truth and two gauges in its premises is given (*Object Aware*). In particular, the dielectric constant of the wall (ε_b) and that of water (ε_w) to evaluate the scattering parameter S_{pqw} , the angle between the sensor line of flight and the projection of the building wall to the ground φ , the radar look angle ϑ , and the height of the local target h before the flooding event and the soil roughness parameters (σ_w and L_w) are required to invert the scattering model as already shown in [17]. The uncertainty on the knowledge of these parameters and the adoption of geometric and electromagnetic models are sources of uncertainty for the flood level retrieval; all these factors have been analyzed, and the relative uncertainty has already been computed in [27]. However, not all the parameters involved in the RCS formulas [see (1)–(7)] are sources of uncertainty; the angle φ , for example, can always be extracted from the SAR images [27], and the radar look angle ϑ is provided in the ancillary data of the SAR image.

All necessary steps for the water depth estimation are summarized in the flowchart in Fig. 2. First of all, a segmentation of the SAR image is performed in order to map the flooded areas and localize the targets of interest (*segmentation block*). Since the segmentation step is not the primary aim of this paper, we used a simple yet effective method already described in [17], but several alternative procedures can be found in the literature such as those in [34] and [35]. According to Iervolino *et al.* [17], in order to distinguish flooded and nonflooded pixels, low- and high-level thresholds are set according to the statistics of the reflectivity relevant to the flooded areas in the image; in particular, the low threshold T_L is set by the mean value intensity μ_I diminished by the standard deviation σ_I , while the high threshold T_H is the sum of the same statistics values

$$\begin{aligned} T_L &= \mu_I - \sigma_I \\ T_H &= \mu_I + \sigma_I. \end{aligned} \quad (10)$$

One of the drawbacks of thresholding is in the likely high rate of false positives as pixels relevant to flooded and shadow areas appear both dark in SAR images; it is possible to separate shadow from flooded zones by choosing a suitable *minimum population value (m.p.v.)*: For example, in this paper, the cluster

Fig. 2. SIObA approach's flowchart. The rounded rectangles represent the input blocks, the rectangles are the process blocks, and the parallelogram represents the electromagnetic choice blocks.

of pixels whose area is smaller than the *m.p.v.* is not considered as flooded even if the pixel intensity falls in the range between the two threshold values. Other choices are possible, but as a general rule, the *m.p.v.* has to be set greater than or equal to the number of pixels of the largest shadow area. In formulas, the *m.p.v.* is given by

$$m.p.v. \geq \frac{S}{\Delta r \Delta x} \quad (11)$$

where S is the shadow area and Δr and Δx are respectively the range and the azimuth pixel spacing.

Finally, the segmented image is obtained by choosing a pixel connectivity rule; it is possible to select a 4-connectivity (each pixel has got only four neighbors: north, south, west and east pixel) or an 8-connectivity (each pixel has got eight neighbors).

Once the segmentation has been performed, it is possible to locate and choose the buildings of interest (*TARGET choice* block). It is assumed that the roughness parameters of the soil, the dielectric constant, and the geometric parameters relevant to the buildings of interest are retrieved by archives (in other words, they are *a priori* known), as later exemplified in Section IV, in order to properly invert (6) or (7). To radiometrically calibrate the SAR image, a multiplicative constant, due to the unknown attenuation, and an additive constant, due to the background additive noise, have to be included [27]. In addition, in the presence of flooding, the height h in (3), which contributes to the dihedral double reflection, is given by the difference between the building height (h_i with $i = A, B, C$) above mean sea level (m.s.l.) and the absolute water level (h_w), which is assumed constant as shown in Fig. 3. Within these hypotheses and based on (3), we are able to write down a system of three equations with three unknowns, the multiplicative constant, the additive constant, and the water depth

$$\begin{cases} \hat{\sigma}_A^0 = c(h_A - h_W) \cdot f(\mathbf{p}_A) + d \\ \hat{\sigma}_B^0 = c(h_B - h_W) \cdot f(\mathbf{p}_B) + d \\ \hat{\sigma}_C^0 = c(h_C - h_W) \cdot f(\mathbf{p}_C) + d \end{cases} \quad (12)$$

where $\hat{\sigma}_i^0$, h_i , and $\mathbf{p}_i$ are respectively the measured RCS relevant to the double reflection contribution, the height, and the

Fig. 3. SIObA approach scenario where the absolute water level (h_W) is the same for the target and for the gauges. The m.s.l. is regarded as absolute reference for all the buildings.

known parameter vector of the i th building in the SAR image (with $i = A, B, C$), c and d are the multiplicative and additive calibration constants, respectively, and h_W is the absolute water level of the flooding previously introduced.

In order to solve the system (12), we need two gauges with different known heights in addition to the building of interest (local target), which are identified in the *GAUGE choice* block in Fig. 2; furthermore, the sum of the local flood level (h_{wi} with $i = A, B, C$) and the building reference height (h_{Ti} with $i = A, B, C$) is assumed constant in the surroundings of the gauges and local target; this assumption makes this approach local. In formula

$$\begin{cases} h_w = h_{wA} + h_{TA} \\ h_w = h_{wB} + h_{TB} \\ h_w = h_{wC} + h_{TC} \end{cases} \quad (13)$$

As anticipated, some parameters involved in the expression of the function $f(\mathbf{p})$ can be retrieved from archives or from any previous relevant SAR image in the absence of flooding (*Archives* block). In particular, ε_w and ε_s are the input of the *Dielectric constant* block which computes $|S_{pq}|$; h_A , h_B , and h_C are evaluated from the *Height Retrieval* block (through optical images or an unflooded SAR image of the same area or land register maps); and k is extracted from the ancillary data of the sensor and, together with the roughness parameters of the soil, represents the input for the *electromagnetic model*

Fig. 4. TIARa approach's flowchart. The rounded rectangles represent the input blocks, the rectangles are the process blocks, and the parallelogram represents the electromagnetic choice blocks.

choice step (rhombus block in the diagram of Fig. 2). Other parameters, instead, have to be computed directly from the SAR images ($\varphi, \hat{\sigma}_A^0, \hat{\sigma}_B^0, \hat{\sigma}_C^0$) and are extracted from the *Double reflection Gauges* and *Double reflection TARGET* blocks.

Once each parameter is known, it is possible to solve the system (12) and obtain the absolute water depth h_W

$$\begin{cases} h_W = \frac{h_A(\hat{\sigma}_C^0 - \hat{\sigma}_B^0)f(\mathbf{p}_A) + h_B(\hat{\sigma}_A^0 - \hat{\sigma}_C^0)f(\mathbf{p}_B) + h_C(\hat{\sigma}_B^0 - \hat{\sigma}_A^0)f(\mathbf{p}_C)}{(\hat{\sigma}_C^0 - \hat{\sigma}_B^0)f(\mathbf{p}_A) + (\hat{\sigma}_A^0 - \hat{\sigma}_C^0)f(\mathbf{p}_B) + (\hat{\sigma}_B^0 - \hat{\sigma}_A^0)f(\mathbf{p}_C)} \\ c = \frac{(\hat{\sigma}_A^0 - \hat{\sigma}_B^0)}{(h_A - h_W)f(\mathbf{p}_A) - (h_B - h_W)f(\mathbf{p}_B)} \\ d = \hat{\sigma}_B^0 - \frac{(\hat{\sigma}_A^0 - \hat{\sigma}_B^0)(h_B - h_W)f(\mathbf{p}_B)}{(h_A - h_W)f(\mathbf{p}_A) - (h_B - h_W)f(\mathbf{p}_B)} \end{cases} \quad (14)$$

Finally, the local water depth can be computed by simply inverting (13) if the topography of the scenario is known

$$\begin{cases} h_{wA} = h_w - h_{TA} \\ h_{wB} = h_w - h_{TB} \\ h_{wC} = h_w - h_{TC} \end{cases} \quad (15)$$

If the gauges are chosen in the premises of the target, the same building reference height can be assumed ($h_{TA} = h_{TB} = h_{TC}$), and therefore, the same local water depth is retrieved ($h_{wA} = h_{wB} = h_{wC}$) as considered in [17]. In conclusion, the approach here presented can be regarded as a generalization of the local approach already shown by the authors in [17].

B. Two Images Area Aware

The TIARa is a global-based approach that relies on a couple of SAR images (*Two Images*), pre- and during/post-event, and permits to retrieve the flood level at a global scale all over the image if an unflooded area in the during/post-event

image is available to perform the calibration (*Area Aware*). The corresponding flowchart for this approach is displayed in Fig. 4. Because of possible different radar views in the pre- and post-event acquisitions, initially, the two SAR images do not match perfectly, and a coregistration procedure is needed to align the pixels in the slave image (post-event) to those in the master image (pre-event) through a *Coregistration* block; at this scope, ground control points are selected, and a nearest neighbor resampling algorithm is applied [36]. The coregistration coherence results are shown in Appendix A. In this case, a further calibration process, in addition to the usual SAR calibration, has to be performed to consider the differences in antenna pointing, orbit track, and radar look angle during two consecutive radar acquisitions. At this aim, a multiplicative constant C has been computed through the *Calibration* block evaluating the double reflection contribution of several buildings located in unflooded areas in both the images (see Appendix B).

As already done for the local approach, it is possible to apply the *Segmentation* block to the coregistered image to separate flooded and unflooded areas and then identify, through the *TARGET choice* block, the targets of interest in whose surroundings the water depth will be estimated.

Applying the model previously described to both images, it is possible to retrieve the post-event building height, considering that

$$\begin{aligned} \sigma_{PRE}^0 &= h_{PRE} \cdot f(\mathbf{p}_{PRE}) \\ \sigma_{POST}^0 &= h_{POST} \cdot f(\mathbf{p}_{POST}) \end{aligned} \quad (16)$$

where σ_{PRE}^0 and σ_{POST}^0 are the RCS relevant to the double reflection line of the coregistered slave and master images, respectively, and h_{PRE} and h_{POST} are the building height in

Fig. 5. Region of interest of Tewkesbury, including the (red rectangular) buildings of interest taken in the (a) HR SAR post-image, (b) HR SAR pre-image, and (c) segmented image. All the images are in the slant range (r)/azimuth (x) plane.

TABLE I
RADAR PARAMETER FOR PRE- AND POST- SAR IMAGES

Parameter	Value
Sensor	TerraSAR-X
Data Product	SSC Complex
Acquisition mode	Stripmap
Look angle [degree]	24
Polarization	HH
Orbit direction	Descending
Side look	Right
Slant range resolution [m]	1.19
Azimuth resolution [m]	3.29
Slant range pixel spacing [m]	2.23
Azimuth pixel spacing [m]	1.71
Carrier frequency [GHz]	9.65

unflooded conditions and the reduced building height in the presence of flood, respectively.

From the ratio of the equations in (16) and including the multiplicative calibration constant C (see Appendix B for further details) to compare the RCS of the pre- and post-images, it is possible to derive (17) to compute h_{POST}

$$h_{POST} = \frac{1}{C} \frac{f(\mathbf{p}_{PRE})h_{PRE}\hat{\sigma}_{POST}^0}{f(\mathbf{p}_{POST})\hat{\sigma}_{PRE}^0} \quad (17)$$

where $\hat{\sigma}_{PRE}^0$ and $\hat{\sigma}^0$ are the RCS estimated from the double reflection contributions of the coregistered slave and master images, respectively, through the *Double Reflection* block.

Also, in this case, it is possible to get all the necessary parameters in order to apply the relations (16) and (17) in the same way already explained for the local approach (from archive, from SAR images, and from ancillary data) through the *Archives*, *Dielectric Constants*, and *Height retrieval* blocks. Finally, the flooding level ($\hat{h}_w$) is evaluated as the difference between h_{PRE} and h_{POST}

$$\hat{h}_w = h_{PRE} - h_{POST}. \quad (18)$$

In the next section, the approaches here presented are applied to two scenarios of interest.

IV. RESULTS

In July 2007, Gloucestershire (U.K.) experienced its worst flood on record, and Tewkesbury, lying at the confluence of the Severn and Avon rivers, was the most damaged town. At that time, one TerraSAR-X Stripmap image (post-image), shown in Fig. 5(a), was acquired on the area on July 25, 2007 and is used in this study. The look angle is 24° , the spatial resolutions are 3.3 and 1.2 m for the azimuth and the slant range, respectively, and the polarization mode is HH. One more image of the same area was acquired in ordinary conditions one year later on July 22, 2008 [see Fig. 5(b)]. This explains why it is called a pre-image as, in principle, it verifies the same (or similar) conditions before the flood occurred, and this is assumed in the following. All acquisition parameters are listed in Table I. The steps explained in the previous section for the threshold segmentation have been applied to the post-image. The aim of this kind of segmentation is to evaluate if the local targets are located in the flooded areas. The segmented image is displayed in Fig. 5(c), where white and black pixels represent respectively flooded and nonflooded areas. It was possible to detect the building targets [red rectangles in Fig. 5(c)] by comparing the segmented image and the coregistered high resolution (HR) SAR images. Two buildings have been chosen as targets: Tewkesbury waterworks (Building 1) and a local factory (Building 2) since both can be considered electromagnetically isolated according to Franceschetti *et al.* [26].

In Fig. 6(a) and (b), the tridimensional model of the targets is reported, while in Fig. 7(a) and (b), an aerial optical image of the flooded buildings is shown. The tridimensional models have been drawn with AutoCAD 2009 software.

In the following, all parameters for the inverse models are evaluated, and finally, the measurement results are shown.

First of all, the different expected backscattering contributions have been considered for both the local targets given the radar parameters. Results are displayed in Figs. 8(a) and 9(a),

(a)

(b)

Fig. 6. Tridimensional view of (a) building 1 and (b) building 2 drawn with AutoCAD 2009 software.

(a)

(b)

Fig. 7. Optical images of (a) building 1 and (b) building 2 in flooding weather condition. Courtesy of BBC News.

(a)

(b)

Fig. 8. Cut at constant azimuth of the scene. (a) Composition of different contributions of building 1 in the SAR image. (b) Detection of the double reflection line in post-event SAR image.

(a)

(b)

Fig. 9. Cut at constant azimuth of the scene. (a) Composition of different contributions of building 2 in the SAR image. (b) Detection of the double reflection line in post-event SAR image.

where all the scattering contributions, relevant to the proposed model, are shown. In particular, the double reflection line of each building is localized by evaluating its distance (expressed in number of pixels) from a landmark: The bank of Severn for the first target and an electricity pole for the second one have been employed as landmarks [see Figs. 8(b) and 9(b)]. The RCS relevant to the double reflection mechanism is estimated with a simple supervised method by the mean intensity of the pixels belonging to the corresponding contribution. Furthermore, from the SAR image, the building orientation angle (φ) has been computed by applying Pitagora's theorem and considering the length of the catheti in azimuth and the slant range pixel spacing.

Geometric parameters (length, width, and height in non-flooded conditions) and information on targets' materials have been directly acquired *in situ* by the authors. The building targets are mostly made of three different materials, i.e., glass, aluminum, and bricks in different percentages, and the dielectric constants of these materials depend on the working frequency (9.65 GHz) [37], [38]. Performing a weighted average of the dielectric constants as done in [38], it is possible to provide a rough estimate of an equivalent mean relative dielectric constant of the wall. The percentage of the materials and their complex relative dielectric constants (ϵ_{Req}) are listed in Table II. The mean relative dielectric constants of the buildings ($\epsilon_{building1}$ and $\epsilon_{building2}$) are

$$\begin{aligned}\epsilon_{building1} &= p_b \epsilon_b + p_g \epsilon_g = 4.55 - j0.29 \\ \epsilon_{building2} &= p_b \epsilon_b + p_g \epsilon_g + p_a \epsilon_a = 5.10 - j3.3 \cdot 10^{-7}\end{aligned}\quad (19)$$

where p_b , p_g , and p_a are the percentages of the materials and ϵ_b , ϵ_g , and ϵ_a are the relative dielectric constants at 9.65 GHz. In addition, the relative dielectric constant of the soil (ϵ_{soil}) in the absence of flooding [39] and that of the water (ϵ_w) have been computed [40] and are shown in Tables III and IV. After that, the Fresnel coefficient first and, then, the module of the scattering element of the building ($|S_{HHb}|$) and of the gauges ($|S_{HHg}|$) in the HH polarization can be evaluated.

The synthetic parameters describing the ground roughness are chosen according to the work by Di Martino *et al.* [32] for normal (pre-event, σ , and L) and flooding (post-event, σ_w , and L_w) conditions; for both cases, neither the GO-PO nor the GO-GO solution is completely fulfilled. However, $k \cdot \sigma > 1$, and $k \cdot \sigma_w > 1$; thus, the GO-GO approximation was certainly the most reasonable approximation between the two; the same assumption is made also in [41] in similar conditions. For the first building target, the values selected to describe the stochastic process of the soil are the same as that in ordinary conditions and flood situation because, in the near surroundings of the building, very high trees and thick vegetation are present; this leads us to assume that there was no relevant change at ground roughness scale.

In order to invert the system (12), two electricity poles are selected as gauges since they can be easily identified in the post-image due to the presence of water. In the SIObA approach, the assumption $h_{TA} = h_{TB} = h_{TC}$ is made, as for [17], for both the buildings since the target and the gauges are really close.

All the parameters computed and necessary to implement the SIObA and the TIARa approaches are listed in Table III (for

TABLE II
RELATIVE COMPLEX DIELECTRIC CONSTANT (ϵ_{Req}) OF THE TARGET MATERIALS AT WORKING FREQUENCY OF 9.65 GHz

Material	Material %		ϵ_{Req}
	Building 1	Building 2	
Glass	3	47	$6.27 - j0.04$
Brick	97	3	$4.53 - j0.31$
Aluminum	-	50	$4.00 - j6.68 \cdot 10^{-7}$

TABLE III
SCENARIO PARAMETERS—BUILDING 1

Parameter	Value (PRE)	Value (POST)
Angle φ [deg]	4.80	4.80
Building height h_{PRE} [m]	13.50	10.97
Relative dielectric constant of the soil $\epsilon_{soil} \cdot \epsilon_w$	$6.6 - j2.8 \cdot 10^{-2}$	$55 - j38$
Relative dielectric constant of building $\epsilon_{building1}$	$4.55 - j0.29$	$4.55 - j0.29$
Element of Scattering matrix $ S_{HHb} $	0.46498	0.79824
Element of Scattering matrix $ S_{HHg} $	<i>Not required</i>	0.55725
Standard deviation σ [m]	0.02	0.02
Correlation length L [m]	0.15	0.15

Fig. 10. Estimation and error parameters.

building 1) and Table IV (for building 2) for ordinary and flood conditions.

We are now able to retrieve the water level by employing (14) for the SIObA approach and (17) and (18) for the TIARa approach and to evaluate the error of measurement by comparing our results with the ground truth. The measurement error is regarded as the difference between the estimated water depth ($\hat{h}_w$) and its true value (h_w). Considering the scenario in Fig. 10, it is possible to write the following expression for the absolute (E) and the relative (e) measurement error:

$$\begin{aligned}E &= |h_w - \hat{h}_w| = |(h_f - h_{uf} - h_{emb}) - \hat{h}_w| \\ e &= \frac{E}{h_f - h_{uf} - h_{emb}}\end{aligned}\quad (20)$$

where h_f and h_{uf} are the water levels measured at the water gauge in flood and unflooded conditions, respectively, while h_{emb} is the height of the river embankment.

The level of the water at the Mythe Bridge water gauge, in the surrounding of the targets, was respectively $h_f = 12.22$ m above m.s.l. on July 25, 2007 (the same day of the SAR image acquisition) [34] and $h_{uf} = 8$ m above m.s.l. in ordinary

TABLE IV
SCENARIO PARAMETERS—BUILDING 2

Parameter	Value (PRE)	Value (POST)
Angle ϕ [deg]	12.7	5.53
Building height h_{PRE} [m]	5.53	2.57
Relative dielectric constant of the soil $\epsilon_{soil} \cdot \epsilon_w$	$6.6 - j2.8 \cdot 10^{-2}$	$55 - j38$
Relative dielectric constant of building $\epsilon_{building1}$	$5.10 - j3.3 \cdot 10^7$	$5.10 - j3.3 \cdot 10^7$
Element of Scattering matrix $ S_{HHb} $	0.64721	1.10707
Element of Scattering matrix $ S_{HHg} $	<i>Not required</i>	0.55725
Standard deviation σ [m]	0.02	0.01
Correlation length L [m]	0.154	0.2

TABLE V
MEASUREMENT RESULTS FOR FLOODING LEVEL
ESTIMATION AND RELATIVE ERRORS

	Building 1				Building 2			
	$\hat{h}_{emb}$ [m]	$\hat{h}_w$ [m]	E[m]	e	$\hat{h}_{emb}$ [m]	$\hat{h}_w$ [m]	E[m]	e
TIArA	2.50	2.53	0.81	0.47	1.50	2.96	0.24	0.09
SIObA	2.50	2.08	0.36	0.21	1.50	3.17	0.45	0.17

Fig. 11. Flood level map of Tewkesbury [34] compared with the outcomes of the current work.

conditions as observed from the visit of the site. Unfortunately, the Severn embankment height for building 1 and the Avon embankment height for building 2 are not known, and only an estimation ($\hat{h}_{emb}$) from the visit of the site is available; for this reason, the measurement errors in (20) are computed by replacing h_{emb} with $\hat{h}_{emb}$.

The estimated embankment heights and the corresponding errors derived by applying both the approaches are shown in Table V. The results show a really good match with the collected ground truth for both the approaches and a measurement error much lower than the spatial resolution (3 m).

TABLE VI
COHERENCE INDEX AND RELATIVE STANDARD DEVIATION FOR THREE
REGIONS OF INTEREST WITH WINDOW DEPTH OF 3 AND 10 PIXELS

	w=3		w=10	
	ψ	σ_ψ	ψ	σ_ψ
Tewkesbury Mythe Bridge	0.838	0.001	0.784	0.101
Tewkesbury Industrial area	0.839	0.091	0.792	0.094
Gloucester	0.832	0.094	0.764	0.095

The results obtained are finally compared with those in [34] where a flood level map of Tewkesbury is derived using the same TerraSAR-X flooded image in combination with a LiDAR DEM of 2-m pixel spacing. Outcomes are consistent for both the buildings: The water depth in the surrounding of the first targets ($\hat{h}_{wT1}$) is between 1.5 and 2.0 m, while it is between 2.5 and 3.0 m for the second one ($\hat{h}_{wT2}$). The level map is finally shown in Fig. 11.

V. CONCLUSIONS AND FUTURE EXTENSIONS OF THE APPROACHES

In this paper, two new methods for flooding level estimation have been introduced with different aims. From an applicative point of view, the SIObA approach looks more adequate to monitor sensible targets such as hospitals, waterworks, or power stations which need to be operative also in emergency situations; on the other hand, the TIArA approach has the potential to retrieve a flood map on the overall scene since only one calibration procedure is required. Obviously, in an operative scenario, a combination of both approaches is envisaged for a monitoring that is able to move from large to small scale at occurrence. In many emergency situations, indeed, this is the current approach where a *global* general assessment is the first step followed soon after by a more detailed *local* analysis.

The first results here presented look very promising, considering that the absolute error in estimating the water level is lower than the azimuth spatial resolution; an even lower error is expected if a Spotlight image were employed since the detection of the double reflection line would be much more accurate in a higher resolution image. Both the proposed approaches have a general applicability. However, there are some recommended guidelines regarding the SAR data set to which these approaches should be applied: HR single look complex data in HH polarization [33] are highly recommended to better detect double reflection lines; multilooking is unadvisable to avoid blurring effects on the double reflection line; the best buildings to select are those with low orientation angle ϕ in order to have a stronger backscattered electromagnetic field.

The estimation procedure is currently supervised in many steps, the most important being the selection of the double reflection contribution. Fortunately, today, the interest for applications derived by the analysis of the double scattering signatures in urban areas has increased, and as a consequence, some research has been carried out on how to effectively and timely automate the detection of the double reflection contribution, such as that in [42] and [43]. That approach can be easily extended and applied to this framework, thus supporting the automation procedure. At the moment, the estimation of the parameters (the orientation angle ϕ , the RCS contribution

Fig. 12. (a) Coherence map and (b) relative histogram for the Tewkesbury Mythe bridge region (scene dimension of 236×245 pixels and $\Psi = 0.784\sigma_\Psi = 0.101$).

Fig. 13. RCS ratio for the 15 calibration buildings.

relative to the double reflection, and the building and gauge heights) involved in (6) and (7) is still supervised; therefore, no conclusion can be drawn about the computational time of the SIObA and TIARa approaches. The authors are currently working on the full automation of both proposed approaches.

There is a need to further test the suggested techniques in more controlled scenarios. This would make them more robust and likely to be used not only in rescue tools but also as support analysis in climate change modeling. Both aspects are considered extremely important and, therefore, the present work is timely, particularly in consideration of the many flooding disasters that occurred in the entire world in the last few years.

APPENDIX A

In this appendix, we evaluate the quality of the coregistration performed in the TIARa approach by computing the coherence index in several areas of the scene. The coherence is the abso-

lute value of the cross-correlation of SAR images normalized to the product of the single autocorrelation square roots [44]

$$\psi = \left| \frac{E[I_1 I_2^*]}{\sqrt{E[I_1 I_1^*]} \sqrt{E[I_2 I_2^*]}} \right| \quad (\text{A1})$$

where I_1 and I_2 are the complex SAR images and ψ is the coherence index with $0 \leq \psi \leq 1$.

This index is unitary if no change in the scene occurred between the two SAR acquisitions and if no coregistration error is present, and it decreases due to scene temporal changes and to coregistration errors [45]. Under the assumption that the process is ergodic and stationary, (A1) can be rewritten as follows:

$$\psi = \left| \frac{\sum_{i=1}^w I_{1i} I_{2i}^*}{\sqrt{\sum_{i=1}^w I_{1i} I_{1i}^*} \sqrt{\sum_{i=1}^w I_{2i} I_{2i}^*}} \right| \quad (\text{A2})$$

where i is the sample number and w is the number of pixels averaged (window depth). The coherence index has been computed with IDL software. The mean has been evaluated with a *smooth* function and considering window depths of 3 and 10 pixels over three different areas in the SAR images: Tewkesbury Mythe Bridge where the buildings of interest are located, Tewkesbury Industrial area not affected by the flood, and Gloucester Centre badly hit by the flood as Tewkesbury. The mean of the coherence index (Ψ) and the relative standard deviation (σ_Ψ) are reported in Table VI, while the coherence map, only for the region of Tewkesbury Mythe Bridge, is shown in Fig. 12.

As expected, the greatest values of the coherence index are got from the Tewkesbury Industrial area because of the lack of the flood; consequently, the pre- and post-SAR images are more coherent. Such high values of the coherence index are an indication of high subpixel accuracy of the coregistration. The

nature of coregistration errors, both in range and azimuth, and the consequent decorrelation between the two SAR images are analyzed in detail in [45].

APPENDIX B

In this appendix, the calibration operation cited in Section III (Methodology) for the TIARa approach is described. The multiplicative calibration constant is evaluated using the contribution of double reflection from 15 buildings to the ratio image of the pre- and post-event amplitude SAR images

$$C = E \left[\frac{\hat{\sigma}_{POST}^0}{\hat{\sigma}_{PRE}^0} \right] \quad (B1)$$

where $\hat{\sigma}_{POST}^0$ and $\hat{\sigma}_{PRE}^0$ are the estimated RCS averaged along the double reflection contribution of each building in the coregistered slave image and the master image, respectively, $E[\cdot]$ is the statistic mean evaluated over the 15 buildings, and C is the calibration constant. The plot in Fig. 13 shows the value of the ratio for each of the buildings employed.

Finally, with the assumption that the process can be considered ergodic, the constant C and its standard deviation can be estimated as follows:

$$C = \frac{1}{15} \sum_{i=1}^{15} \left(\frac{\hat{\sigma}_{POST}^0}{\hat{\sigma}_{PRE}^0} \right)_i = 0.82$$

$$\sigma_C = \sqrt{\frac{1}{15} \sum_{i=1}^{15} \left| \left(\frac{\hat{\sigma}_{POST}^0}{\hat{\sigma}_{PRE}^0} \right)_i - C \right|^2} = 0.11 \quad (B2)$$

where i is the sample number (i th building). The standard deviation tends to zero when the number of buildings increases.

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