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ANALYSIS OF THE PERFORMANCE OF SWASH IN HARBOUR DOMAINS

JOAN ALABART[(1)], AGUSTÍN SÁNCHEZ-ARCILLA[(2)] & GERBRANT VAN VLEDDER[(3)]

[(1)] *ETSECCPB, Barcelona, Spain and TU DELFT, Delft, The Netherlands, j.alabart.llinas@gmail.com*

[(2)] *ETSECCPB, Barcelona, Spain, agustin.arcilla@upc.edu*

[(3)] *TU DELFT, Delft, The Netherlands, g.p.vanvledder@tudelft.nl*

Abstract

Wave penetration inside harbours has been one the main issues that port planners and engineers have had to deal with in recent years. Wave conditions inside harbours trigger vessel movements, create dynamic loads on port structures and condition harbour exploitation and safety. For this reason in the recent past maritime and port engineers have developed a set of semi-empirical criteria and physical modelling tools to design the layout of breakwaters and other protection structures. Nevertheless, with the development of computers and numerical methods, several models have tried to simulate the propagation of waves inside such restricted domains, affected by multiple processes such as diffraction, partial reflection, etc. It is in this framework where SWASH (Simulating WAves till SHore), a model developed by TU Delft, is expected to perform realistic and accurate simulations well beyond the performance limits of other state-of-the-art codes.

SWASH solves directly the momentum conservation laws and can deal with dyke geometry and porosity. It is very suited for simulating non-hydrostatic, free-surface flows, including long-wave generation and short wave propagation. Because of that we shall here evaluate how such a model can simulate the propagation of various types of waves in real harbour cases. The Port of Blanes, located in the Catalan coast, where wave measurements were available, was chosen as our test case. The wave climate recorded offshore the harbour entrance was introduced as model boundary condition, together with features of the harbour structures. The output from the model was then compared to the actual measurements inside the Port.

The results show that SWASH can be indeed a rather useful tool for harbour engineering, providing realistic and accurate results. Furthermore, the way the model accounts for porous structures can be considered to be quite flexible and realistic.

Finally some conclusions and recommendations for further work in this topic have been drawn and will be presented in the paper. This will set the basis for further development of this numerical tool that could become the cornerstone of port layout planning in the coming years.

SWASH; Waves; Modeling; Harbor; Blanes

1. Introduction

The development of ports has been a major indicator of the development of the society as via them goods were imported and exported and enhanced the spreading of culture and science all over the world. In the modern times though, the layout of ports has little to with the former harbors built by our ancestors. Nowadays, the design of a port is done according to multiple criteria that range from hydraulic engineering, to economic analysis, passing through transport chains, logistics, structural design, risk assessment, environmental assessments and many other factors. Despite all these requirements, the main goal of the infrastructure planning is to provide a basin where vessels can operate safely for a sufficient amount of time.

That is one of the reasons why maritime engineers have been studying the behavior of waves, how they propagate towards the coast, which phenomena occur and how those movements affect the transports of sediments along the shore line; how the waves penetrate into harbor basins and affect the movements and safety of the ships and operations in harbor basins, and many other applications.

In order to provide the optimum design of a port, several empirical guidelines are available and have been used until the development of computers. However, at present with the development of numerical methods, more accurate models try to reproduce this complex reality that those early studies and guides simplified.

Is within this framework where SWASH, the model developed by TU Delft, appears. Before it this university had developed other models like HISWA or SWAN which have their own scope of application, but were not intended to reproduce the effects that occur in places with rapidly varying proprieties. Besides, as it is the case in harbor domains where the effects of diffraction and reflection play a major role, the SWASH model is able to model the required processes.

Thus, SWASH being a different model than SWAN, is thought to be able to reproduce satisfactorily the propagation of waves inside ports and hence, become an important tool in port planning and design.

To analyze the performance of this model in such restricted domains, the measurements obtained by an offshore buoy were used as input for the model. In addition, the bathymetry of the port and the surrounding area were obtained and adapted to the model together with porous layers representing the port structures. Nonetheless, an intermediate step was the propagation of the waves with SWAN towards the entrance of the port, and the use of its output as input for the actual SWASH model. Finally, a comparison between the real measurements inside the port and the output results was done.

In the process special attention was paid to the treatment of the porous structures when it comes to the SWASH model and the problems of stability that may arise and how they were solved in this project.

2. Limits of conventional wave analysis

When propagating waves in harbor domains, there are many physical phenomena that have to be simulated. These are mainly shoaling, diffraction, interaction with porous structures witch yields partial reflection, refraction, transmission and energy dissipation, wave breaking and non-linear effects such as wave asymmetry and wave steepening due to the shallow water nature of port domains. In addition it is important to take into account that waves are rarely monochromatic and unidirectional. Therefore it is important to incorporate frequency and directionally spread wave fields in the boundary conditions. In addition, other mechanisms that are able to dissipate wave energy are also necessary.

The departure point of all models available are the Navier-Stokes equations derived from Newton's second law and the assumption that the fluid stress is the sum of a diffusing viscous term and a pressure term. As those equations are nowadays still unsolvable, many simplifications and assumptions are done which define the features of the different models. They can be illustrated by spectral wind-wave models for wave propagation in open water, parabolic mild-slope equation models for wave propagation in large coastal areas with negligible reflection, elliptical mild-slope models in waters of varying depth, models that use the Helmholtz equation for harbor resonance and wave agitation and Boussinesq models for non-linear wave refraction-diffraction in shallow waters (Nwogu & Demirbilek, 2001). Nonetheless, in general two main model families can be found when referring to the approach followed to represent the wave field (Battjes, 1994). These are the phase average models (e.g. WAVEWATCH, WAM and SWAN) that operate in the frequency domain and are based in the wave action equations and the phase solving models (e.g. SWASH) that operate in the time domain calculating the position of the sea surface elevation field (Guzmán, 2011).

Phase average models do not determine the exact location of the sea surface elevation and the results correspond with a picture of the wave field average characteristics. Furthermore, they are not able to reproduce reliable simulations neither of diffraction nor other non-linear effects. In general they do not require much computational effort. For these reasons they are appropriate in mid to large domains with slowly varying environments with weak variations of the wave properties within a wavelength scale, allowing the wave field to be considered quasi-uniform (Guzmán, 2011).

On the other hand, phase solving models yield as output a set of surface elevation fields for each time step. They require post processing to obtain important parameters such as the wave height and period. Moreover, they are much more accurate when accounting for domains where local wave properties vary strongly in distances smaller or similar to the wave length. In contrast to phase-resolving models they are much more expensive computationally as they describe the sea surface in time and space. For this reason, they are applied in small domains where they are strictly needed as in harbor basins.

3. The SWASH model

SWASH is a general-purpose numerical tool for simulating non-hydrostatic, free surface, rotational flows. It provides a general basis for describing complex changes in rapidly varied flows and wave transformations in coastal waters. This recently released model has been developed at TU Delft. It is an open source model and new versions become regularly available. The version used in this paper is 1.20.

This model is based on the hyperbolic Non-Linear Shallow Water equations including a non-hydrostatic pressure term (Zijlema & Stelling, 2008). With those equations, all the main propagation wave physics are contained and no approximations are neither needed nor added as source or sink terms. It is based on an explicit; second order finite differences method for staggered grids and this is why mass and momentum are strictly conserved at a discrete level. In addition when it comes to the time integration it uses an explicit method. To solve the instability issues that may arise from this type of numerical schemes, the time step is adapted (double or halved) so in every loop it satisfies the Courant-Friedrichs-Lewi condition (Courant number). It can be run either in depth-averaged mode or multi-layered mode. Thus, instead of increasing the frequency dispersion by increasing the order of derivatives of the dependent variables like Boussinesq-type models (e.g. BOUSS 2D); SWASH accounts for it by increasing the number of vertical layers containing at most second order spatial derivatives.

Summarizing SWASH considers the following physical phenomena: wave propagation, frequency dispersion, shoaling, refraction and diffraction, non-linear wave-wave interaction, wave run-up and run-down, wave breaking, moving shoreline, bottom friction, partial reflection and transmission, wave-induced currents and wave-current interaction, vertical turbulent mixing, subgrid turbulence, mass and momentum conservation and rapidly varied flows.

However, it presents some limitations. The current version does not account for wind effects on wave transformation. Furthermore, as SWASH is based on a finite differences scheme, for now it is not possible to use unstructured meshes.

4. Porous layers

Coastal structures like breakwaters and vertical quays have different reflective and transmission characteristics. These are difficult to model, and the SWASH model provides a mechanism to do this by means of porous structures.. The treatment of such elements is, therefore, a cornerstone for the models whose scope is those restricted areas. Previous models like the widely used SWAN accounted for it by including frequency dependent reflection and transmission coefficients. However, in reality there are many more factors that define the amount of energy that is transmitted, reflected or dissipated such as the wave height, the period, the angle of incidence and the size of the structural elements. A key difference between SWASH and SWAN is that SWASH models the hydro-dynamic properties of coastal structures leading to a certain amount of wave dissipation, reflection and transmission, where in the SWAN model these quantities are explicitly described. That is the reason why SWASH has a totally different approach to account for porous structures. The model includes the Forchheimer relations in the porous momentum equations by means of two extra dissipative terms, a linear one f_l and a turbulent one f_t. These terms depend on the porosity n, the viscosity υ, the element size D_{50}, and the flow mean horizontal velocity u. In addition the two Forchheimer parameters α and β are also included. This yields equations [1] the horizontal momentum conservation law with these two extra dissipative terms. The SWASH manual (SWASH_team, 2013) gives insight on these parameters.

$$\frac{1}{n}\frac{\partial u}{\partial t} + \frac{1}{n^2}\frac{\partial u^2}{\partial x} + \cdots + f_l u + f_t u|u| = 0 \qquad [1]$$

where,

$$f_l = \alpha_E \frac{(1-n)^3}{n^2}\frac{\upsilon}{D_{50}{}^2} \quad , \quad f_t = \beta\frac{1-n}{n^3}\frac{1}{D_{50}} \qquad [2]$$

In order to check how SWASH accounts for porous structures, several simple 2D cases were tested changing the parameters either from the structure itself or from the incoming waves. Initially the waves were inputted as propagating perpendicularly towards the porous layer. The domain was 300x300 m^2 with a porous structure of 2m width located at 200m from the incoming boundary condition; the depth was constant and equal to 10m. The input wave height was 0,05m. The wave height transmission and reflection coefficients were then calculated. Figure 1 shows the evolution of these coefficients with varying porosity and element size.

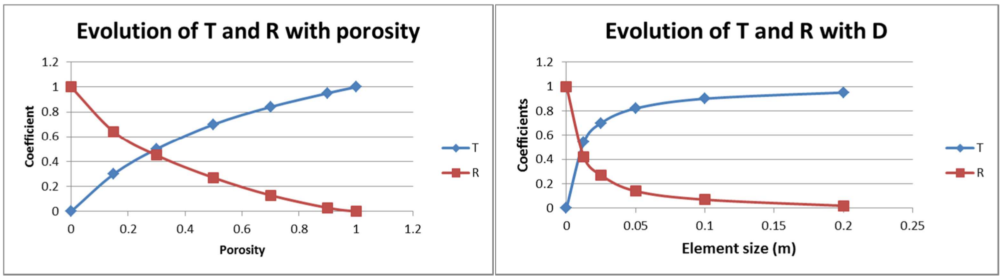

Figure 1. Evolution of the transmission (T) and reflection (R) coefficients with the porosity (left) and the element size (right).

However, when trying to use porous layers to model porous structures in 2D realistic cases, instability problems occurred as illustrated in figure 2. Thus, a 1D systematic analysis of the stability of SWASH when simulating domains with porous structures was done. Two alternatives were considered; on the one hand to model the structures as a steep variation of the bottom without including porous layers and on the other hand as a porous layer maintaining the bottom smooth (without the port structures on it). Different grid sizes where used and both regular and irregular waves introduced. It was seen that when reducing the grid size, the simulation became more unstable although the results were better when using porous layers than when using steep variations of the bottom.

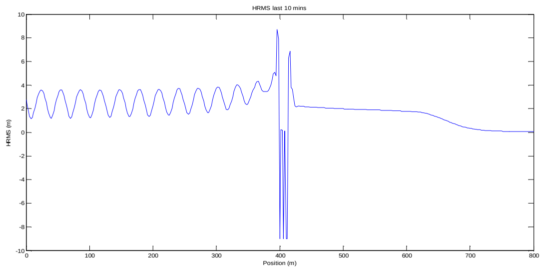

Figure 2. Instability around the porous structure.

Once these problems were observed, a series of trial and error simulations changing the numerical settings for the discretization of the equations were done. The model offers many options when it comes to this setting ranging from upwind first order schemes to higher order κ-schemes or centered ones. Furthermore, the default scheme for the horizontal advective terms is the second order backward upwind scheme (BDF). From this analysis it was found that the simulations were always stable when using one vertical layer and a first order upwind discretization both for the u/v and the w momentum conservation equations. In addition, the discretization for water depth in velocity points was also set to first order scheme. These results were tested in 2D simulations and used in the real case object of this study. The use of multiple vertical layers was discarded because the domain was in relatively shallow waters (maximum water depth of 13m) and because it was seen that it increased the instability of the simulations.

5. Port of Blanes case study

The election of the port of Blanes as the case study was due to the fact that this was a project carried on between the UPC and TU Delft and the former university had an extensive series of data for the abovementioned harbor. This small harbor is located in the Catalan Coast 70km north from Barcelona and underwent an expansion that finished in June 2012. The overall dimensions of the port are roughly 500x500m² (Figure 3).

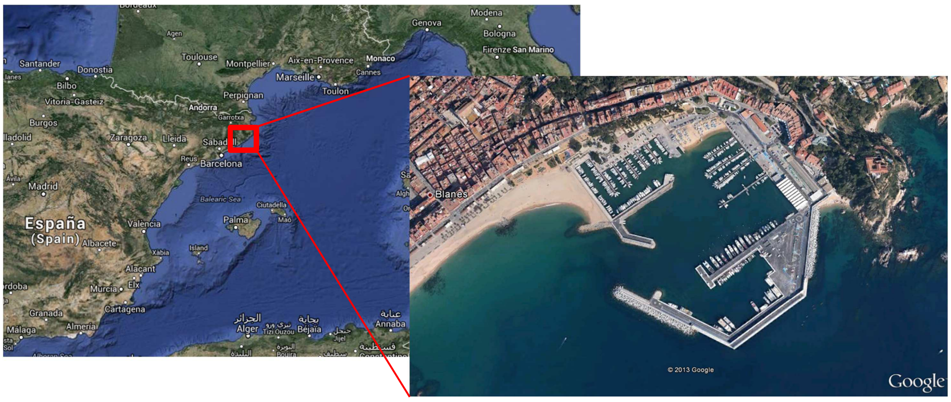

Figure 3. a) Location of Blanes in the Spanish Mediterranean Coast. b) Aerial view of the port of Blanes. Source: Google Maps.

Two sets of data have been used. On the one hand, a buoy record during the year 2011 with hourly registration and post-processing yielding spectral parameters. The data came from the XIOM network buoy deployed at 41º 38,81'N – 2º 48,93'E which is at 3,1km from the entrance of the port. A 20 years wave record of a buoy located at around 25km from the port from Argoss was also used. The first set of data was employed to test the model whereas the second one was used to analyze the wave climate.

5.1 Long term normal wave climate

The wave climate in Blanes was analyzed in two ways. First of all, an analysis of the wave direction of propagation, wave height and frequency of occurrence was done and synthetized in Figure 4, left panel. Furthermore, to analyze the extreme wave climate, the POT method was used with a threshold of a wave height of 2m and a minimum time between storm peaks of 72h. Afterwards a linear regression analysis of the frequency of occurrence of the wave heights was done. The results are shown in Figure 4, right panel.

Nevertheless, when analyzing the extreme wave climate, it was seen that the storms mainly came from the East, South East and South. Therefore it was decided to test the performance of SWASH with waves coming from these directions with different spectral parameters.

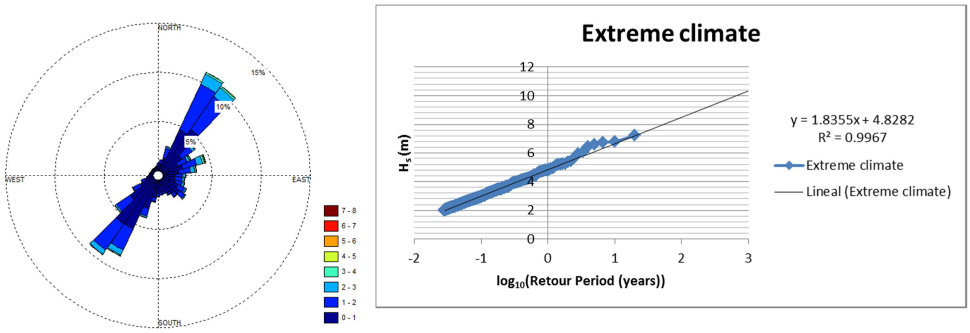

Figure 4. Left: Wave rose off the port of Blanes. Right: Extreme climate linear regression.

5.2 Bathymetry

To perform the simulations two sets of bathymetry were necessary, one for the SWAN deep water propagation, and another for the shallower wave propagation with SWASH.

For the simulations with SWAN, the bathymetry was obtained from the Admiralty Charts. The domain was from 2,75º to 2,85º E and from 41,6º to 41,7º N with an accuracy of 0,0005º that yielded a grid size of dx=42m and dy=56m.

For the simulations with SWASH, the bathymetry was obtained from the LIM-UPC database though it was not fully up to date, not including the new structures constructed during the expansion of the port. Hence a modification and adaptation of the available data was done so that the new structures could be included (see figure 5).

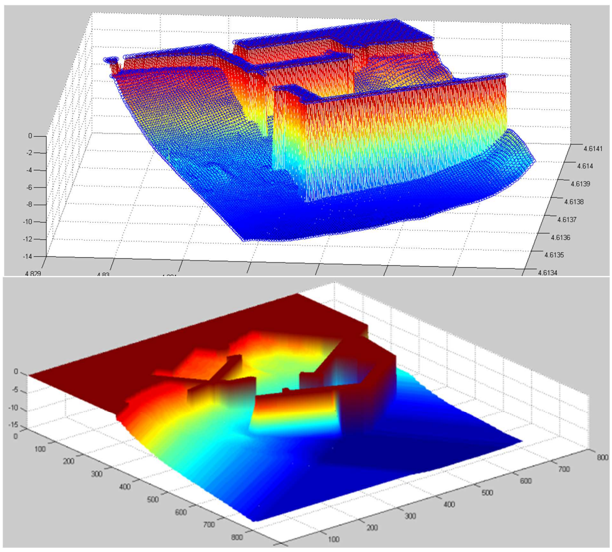

Figure 5. Up scatter plot of the provided bathymetry Down 3D plot of the adapted bathymetry including the new port structures.

5.3 SWAN wave propagation

The simulations were split in two domains as shown in Figure 6.

Figure 6. SWAN and SWASH domains. Source: Google Maps

The simulations with SWAN lasted 1h with a domain of 5.000x3.000 m^2 and a grid size of 10m. The grid was tilted 46º to adjust better to the wave propagation direction. The wave climate was inputted using a JONSWAP spectrum introducing the significant wave height, the peak period, the mean direction and the directional spreading. The outputs were requested at the point where the simulation with SWASH would have the southern boundary condition. In total 6 simulations with storm episodes coming from the east, south-east and south in January and December of 2011 were done.

5.4 SWASH wave propagation

The last step was the propagation of waves within the port. To do so a domain of 1000x800 m^2 was defined with a grid size of 2m. Knowing that the wave length was about 60m there were 30 grid points per wave which was reasonable. The waves were inputted only in the southern boundary as a JONSWAP spectrum (from the outputs of SWAN). One vertical layer was used and the numerical discretization found in the stability studies was implemented. In addition sponge layers were located in the west, north and east boundaries which were set as radiation boundaries to be able to dissipate the waves. Bed friction and horizontal viscosity were considered as well. Moreover, to increase stability the limits of the Courant condition were set as 0,1 and 0,5. Wave breaking was considered as well.

When it comes to the port structures two options were considered. The first one was to include the porous structures in the bottom file (the bathymetry) not allowing any transmission and therefore enhancing reflection. The other option was to smooth the bathymetry and include the port structures as porous layers. The first option was discarded because it produced too much reflection and an unrealistic accumulation of energy in front of the structures. The second option, which was much more flexible, was therefore selected. In all the simulations, since the port structures were mainly vertical dykes without allowing energy transmission, the porosity was set to 0,01 and the element size to 0,025m. The duration of the simulation was 20mins. The output was a map of the H_{RMS} in the whole domain during the last 10 minutes of the simulation once the wave field could be considered stationary. Figure 7 shows the results from a case where the input for SWASH was an spectrum with Hs=2m, Tp=6,63s, θ=150º and a directional spreading of 26,4º. It can be seen how the waves come from the south-east, bounce against the dykes and produce stationary wave patterns, enter the port because of diffraction and produce stationary waves inside the basins with its nodes and antinodes. It can also be seen how the artificial beaches located in the surroundings of the port dissipate the energy through wave breaking.

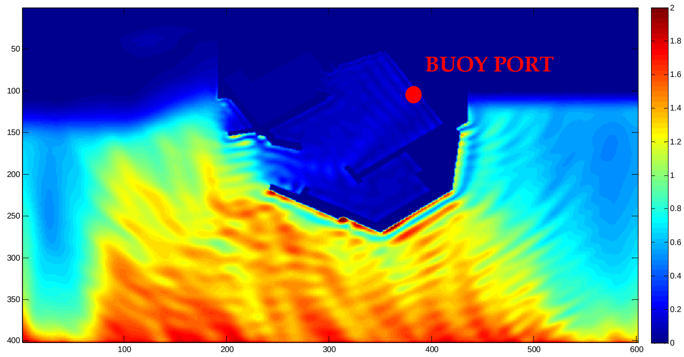

Figure 7. HRMS map of the wave penetration in the port of Blanes.
Case of the 28th of January 2011 at 01h.

5.5 Comparison of results.

Table 1 shows the comparison between the simulation and the buoy measurements inside the port. These results must be analyzed bearing in mind the following aspects:

- SWASH was not the only model used, SWAN might have produced some errors as well;
- the bathymetry was adapted and might induce further errors;
- the location of the buoy inside the port was allowed also for some variations and the observed standing wave pattern in the basins might produce big variations of the results.
- due to these considerations a tendency to underestimate the Hs inside the port can be observed in the model results.

Table 1. Comparison of results between the model simulations and the real buoy measurements.

CASE	**HRMS (SWASH)**	**Hm0s (SWASH)**	**Hm0 (buoy)**	**Absolut error**	**Relative error**
	(cm)	(cm)	(cm)	(cm)	(%)
Blanes011	24.5	34.7	42.7	**-8.07**	**18.8**
Blanes012	32.3	45.8	34.7	**11.0**	**31.7**
Blanes013	19.8	28.1	51.8	**-23.7**	**45.7**
Blanes02	13.9	19.7	21.6	**-1.94**	**8.96**
Blanes021	2.37	3.35	15.4	**-12.0**	**78.3**
Blanes022	8.23	11.6	17.2	**-5.61**	**32.5**

6. Conclusions and recommendations

The conclusion of this study is that SWASH is indeed an extremely valuable tool when it comes to the modeling of wave propagation inside harbor domains. It is stable and produces realistic and accurate results. However, this model is still in the early phases and has still some issues that need further attention like the discretization schemes. Nonetheless, the actual version 1.20 has been proved to be capable of dealing with complex two-dimensional cases.

The first recommendation that arises from the study is that to be able to validate the model, it is necessary to dispose of an accurate bathymetry, buoy measurements next to the port entrance, and wave measurements at several locations within the port.

It is also suggested to improve the input data in the boundary conditions because nowadays in the same boundary the wave data inputted is the same no matter what the depth is. This creates unrealistic boundary conditions if the boundary condition has not a uniform depth.

In addition, when it comes to porous layers, nowadays SWASH applies the same values of the porosity, element size and the Forchheimer α and β parameters in the whole height of the porous structure. It is suggested to allow different values for the different vertical layers to be able to model more accurately port structures. Furthermore, the Forchheimer dissipative terms should be included also in the vertical momentum equation.

Ultimately, when it comes to the use of SWASH in harbour domains, it is suggested to use the first order discretization scheme that is abovementioned, model the port structures as porous layers, set the grid size to 1 or 2m, create sea level maps every 1s to be able to see how the model is working, include sponge layers in the dissipative boundaries with at least a width of 200-300m. At last but not least, it is important to keep in mind the goal of the simulations not going into much detail in aspects that will not play a role in the output results.

Acknowledgments

The realization of this project has been possible thanks to the Catalonia University of Technology BarcelonaTech (UPC), the Technische Universiteit Delft (TU Delft), the Erasmus Exchange program, and the COVARIANCE project (CTM2010-19709-MAR - J01541).

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