Production of Digital Terrain Models for the Dutch Caribbean

Implementation for Saba & St Eustatius

Sander Mücher, David Jonker, John Stuiver, Henk Kramer and Erik Meesters

ALTERRA
WAGENINGEN UR

Production of Digital Terrain Models for the Dutch Caribbean

Implementation for Saba & St Eustatius

Sander Mücher[1], David Jonker[2], John Stuiver[3], Henk Kramer[1] and Erik Meesters[4]

1 Alterra – Wageningen UR

2 Dotka Data

3 Wageningen University

4 IMARES – Wageningen UR

This research was funded by the Dutch Ministry of Economic Affairs (project number BO-11-011.05-027 , Alterra project number: 5240638-01).

Alterra Wageningen UR
Wageningen, october 2014

Alterra report 2569

Mücher, S., D. Jonker, J. Stuiver, H. Kramer, E. Meesters, 2014. *Production of Digital Terrain Models for the Dutch Caribbean; Implementation for Saba & St Eustatius.* Wageningen, Alterra Wageningen UR (University & Research centre), Alterra report 2569. 40 pp.; 30 fig.; 4 tab.; 13 ref.

Abstract NL De BES eilanden (Bijzondere Eilandelijke Status, wel te verstaan Bonaire, St Eustatius en Saba) in het Caribisch gebied zijn sinds Oktober 2010 Nederlandse gemeenten geworden. Deze eilanden vormen een hotspot wat betreft biodiversiteit. Dit brengt specifieke verantwoordelijkheden met zich mee, waaronder een gedegen natuurbeleidsplan. Elk plan en de monitoring hiervan vraagt om goede basiskennis en -data. Naast goede topografische kaarten is het voor veel studies van groot belang om goede hoogtekaarten te hebben. Gedetailleerde hoogtekaarten zijn van belang niet alleen voor de pre-processing van zeer hoge resolutie satellietbeelden, maar ook voor bijv. geomorphologische studies, bodemkundige surveys, hydrologische modelering, soorten niche modellering die allen gebruik maken van hoogte informatie. Met name voor Saba en St Eustatius, met een zeer gevarieerd en complex reliëf, zijn accurate hoogtekaarten van groot belang. Binnen dit project zijn gedetailleerde hoogtekaarten voor Saba en St Eustatius op basis van stereo-interpretatie van luchtfoto's gemaakt. Daarnaast heeft dit project geleid tot een orthophoto-mosaic (dat wil zeggen gecorrigeerd voor hoogte-effecten) van de luchtfoto's met een 20 cm detail die ook voor allerlei doeleinden ingezet kan worden. Dit rapport geeft in het kort weer de materialen en methoden die gebruikt zijn bij de vervaardiging van de verschillende producten.

Abstract UK Bonaire, St Eustatius and Saba islands of the Caribbean Netherlands became Dutch municipalities in October 2010. These islands are considered a hotspot of biodiversity. This brings along specific responsibilities, including a thorough conservation plan. Each plan and monitoring of its progress demands good basic knowledge and data. It is of great importance for many studies to have detailed altitude maps, in addition to good topographical maps. Detailed elevation maps (Digital Terrain Models, DTMs) are important not only for the pre-processing of very high resolution satellite imagery, but also for e.g. geomorphological studies, soil surveys, hydrological modelling, species niche modelling, that all need altitude information as an input. At present there are no detailed digital terrain models for these islands, which is especially important for Saba and St Eustatius with a very varied and complex topography. For this reason the project aimed at the production of a very detailed digital terrain model based on stereoscopic interpretation of aerial photographs for Saba and St Eustatius. Besides the production of the DTMs, the project resulted also in the production of an orthophoto-mosaic for both islands on basis of the aerial photographs with a 20 cm detail. This report describes the materials and methods that have been used for the creation of the different products.

Keywords: aerial photography; stereoscopy; triangulation; point clouds; DTMs; interpolation methods.

The pdf file is free of charge and can be downloaded via the website www.wageningenUR.nl/en/alterra (go to Alterra reports). Alterra does not deliver printed versions of the Alterra reports. Printed versions can be ordered via the external distributor. For ordering have a look at www.rapportbestellen.nl.

Alterra report 2569 | ISSN 1566-7197

Photo cover: Photo cover: A 3D visualisation of the produced Altitude map overlayed with the orthophoto mosaic with a 20 cm resolution for a part of the island Saba.

Contents

Preface

The project was a collaboration between Alterra, IMARES, Dotka Data and Wageningen University. The project was financially supported by the Dutch Ministry of Economic Affairs (project number BO-11-011.05-027). Since detailed altitude maps were missing and urgently required for the Dutch Caribbean islands St Eustatius and Saba, a project plan was written aiming at the production of DTMs for these two islands. This project can be seen as a pleasant and good collaboration between research institutes, a private enterprise and a university.

Summary

Bonaire, St Eustatius and Saba, islands in the Caribbean, became Dutch municipalities in October 2010. These islands are considered hotspots of biodiversity. This brings along specific responsibilities, including a thorough conservation plan. Each plan and monitoring of it demands good basic knowledge and data. It is of great importance for many studies to have proper altitude maps, in addition to good topographical maps. Detailed elevation maps (Digital Terrain Models) are important not only for pre-processing of high resolution satellite imagery , but also for e.g. geomorphological studies, soil surveys, hydrological modelling, species niche modelling, that all need altitude as an important input data layer. At present there are no detailed digital terrain models for these islands, while these are especially important for Saba and St Eustatius that have a very varied and complex topography.

Since these DTMs were missing, a project plan was written aiming at the production of DTMs for these two islands financed by the Dutch Ministry of Economic Affairs. A spatial detail of a few meters, with an accuracy of height in meters, was required. Stakeholders are local administrative and conservation organisations (e.g. STENAPA, SCF), NGO's and research institutes like Alterra and IMARES. The production of the DTMS for Saba and St Eustatius and associated methodologies are being described in this report. The project was a collaboration between Dotka Data, Wageningen University and the agricultural research institutes IMARES and Alterra (DLO). The first stage concerned the stereoscopic interpretation of the aerial photographs of 1991 with a 20 cm resolution and the conversion into 3D point clouds (so called las files). This first phase has been executed by Dotka Data. In this stage the influence of the vegetation has been removed as far as possible to determine the absolute height of the ground surface. Due to the dense vegetation on some parts of the islands it was not always possible to find bare ground. As a consequence, it was not always possible to completely remove the influence of the vegetation. The second stage concerned the conversion and interpolation of the las point cloud files into a wall-to-wall map of the terrain (DTM) with a grid resolution of 5 meters and height information in meters. The second phase has been implemented by Wageningen University and Alterra. The final step, the production of orthophotos (20 cm spatial resolution), which have been corrected for the influence of height, has been implemented by Dotka Data on basis of the DTMs provided by Alterra. The production process of the DTMs has been hampered to some degree by the lack of useful ground control points (GCPs) with an absolute measurement of x, y and z values. These GCPs are necessary for an absolute calibration and should be well distributed over the islands. The GCPs that were available from the early nineties could unfortunately not be recognized on the aerial photographs of 1991. In other words, no GCPs could be used to correct the calculated height values. Therefore a pragmatic solution has been used in which the sea level has been used as a reference to an absolute height of zero meters. An additional 3D triangulation was needed for St Eustatius to place the complete shore line as good as possible at sea level. All production steps of the DTMs and ortho-mosaic, including the final results are discussed in this report. In an ideal situation the DTMs should have been produced on basis of LiDAR altimeter measurements as is being used for the production of AHN (Dutch: Actueel Hoogtebestand Nederland; English: the current elevation map of the Netherlands).

1 Introduction

1.1 Background

The Caribbean islands Bonaire, Saba and St Eustatius became special municipalities of the Netherlands on the 10th of October 2010 and are a hotspot of biodiversity. This brings specific responsibilities, amongst other good nature and spatial planning. For proper implementation of policies and monitoring consistent spatial data layers are needed. One of these essential spatial data sets are digital terrain models. Digital Terrain Models (DTMs) are amongst others essential for a good pre-processing of very high resolution satellite imagery to surface reflectance, but also for geomorphological studies, soil surveys, hydrological modelling, niche modelling of species, etc.

At this moment, there is a lack of spatially detailed DTMs for especially Saba and St Eustatius which have a large variation in altitude and have a complex relief. Since these DTMs were missing, a project plan was written aiming at the production of DTMs for these two islands financed by the Dutch Ministry of Economic Affairs. A spatial detail of a few meters, with an accuracy of height in meters, was requested. The production of the DTMs for Saba and St Eustatius has been implemented on basis of collaboration between Dotka Data, Wageningen University and the agricultural research institutes IMARES and Alterra (DLO). The stereoscopic interpretation of the aerial photographs with a 20 cm resolution and the conversion into 3D point clouds (las files) has been executed by Dotka Data. The conversion and interpolation of the LAS files to DTMs was implemented by Wageningen University and Alterra. In Addition, orthophoto-mosaics were produced by Dotka Data on the basis of the DTMs provided by Alterra. The production steps of the DTMs and ortho-mosaics are discussed in this report.

1.2 Study area

The Dutch Caribbean islands, Bonaire, Saba and St Eustatius are located in the Caribbean Sea. St Eustatius and Saba both belong to the Leeward islands. St Eustatius and Saba differ climatologically significantly from Bonaire, as the annual rainfall and susceptibility to hurricanes of these two islands is higher (Debrot & Sybesma, 2000).

Below a short description is given of the two islands St Eustatius and Saba for which Digtal Terrain Models (DTMs) have been created on basis of stereo-interpretation of aerial photographs from 1991 with a 20 cm spatial resolution.

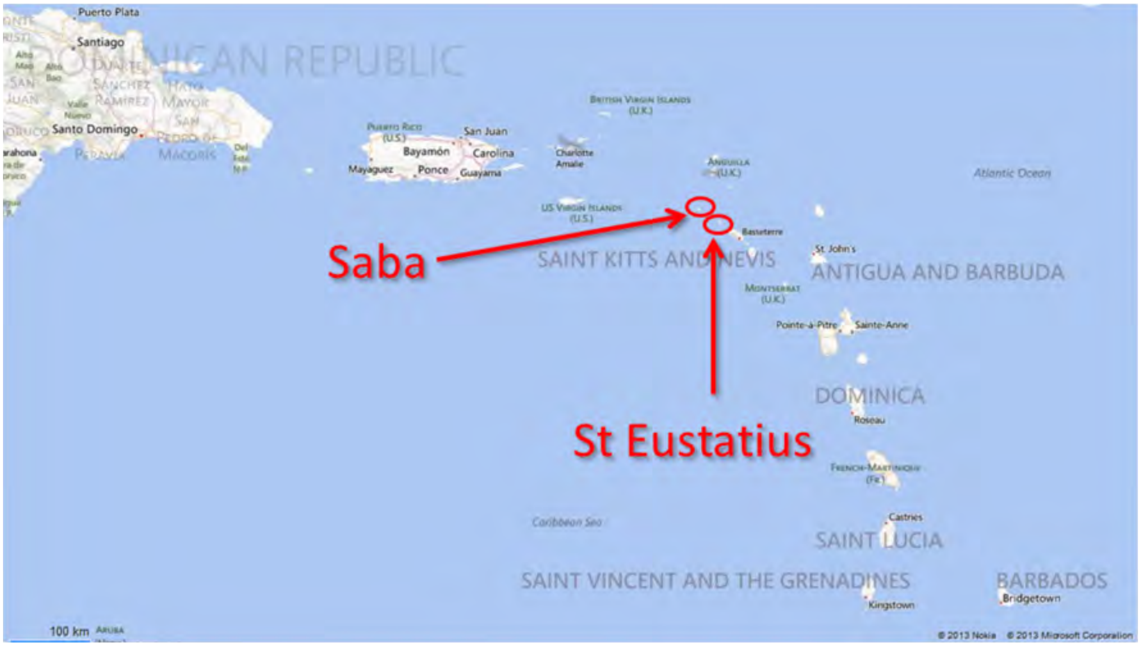

Figure 1 *Location of St Eustatius and Saba in the West Indies (source: Bing maps).*

1.2.1 St Eustatius

St Eustatius is a small island in the Caribbean and belongs to the northern part of the Leeward islands, situated in the West Indies. Its location is between 17°28' and 17°32' N latitude and between 62°56' and 63°0' W longitude (De Freitas et al., 2012). St Eustatius is also known as Statia by the local community.It received special status as a special Dutch municipality in 2010 and has approximately 3,500 inhabitants (167 inhabitants per square kilometre). It is a volcanic island with a total area of 21 km^2.

The highest peak is at the 602 meter high dormant volcano The Quill. St Eustatius has a tropical climate with an annual rainfall of 986 mm, with the majority of precipitation falling between August and November (Collier & Brown, 2006). The wind blows predominantly from the northeast to southeast (more than 80% of the time), with wind speeds at levels 3 and 4 on the Beaufort scale (Debrot & Sybesma, 2000). Monthly mean temperature is about 26.7°C with a maxima of 30°C and a minima of 24°C (Debrot & Sybesma, 2000). Annual sea surface water temperature varies from 24.7°C (February) to 27.9°C (September) (Debrot & Sybesma, 2000). The vegetation on St Eustatius consists primarily of thorn woodland and grassland, with evergreen and elfin forest within The Quill (Collier & Brown, 2006).

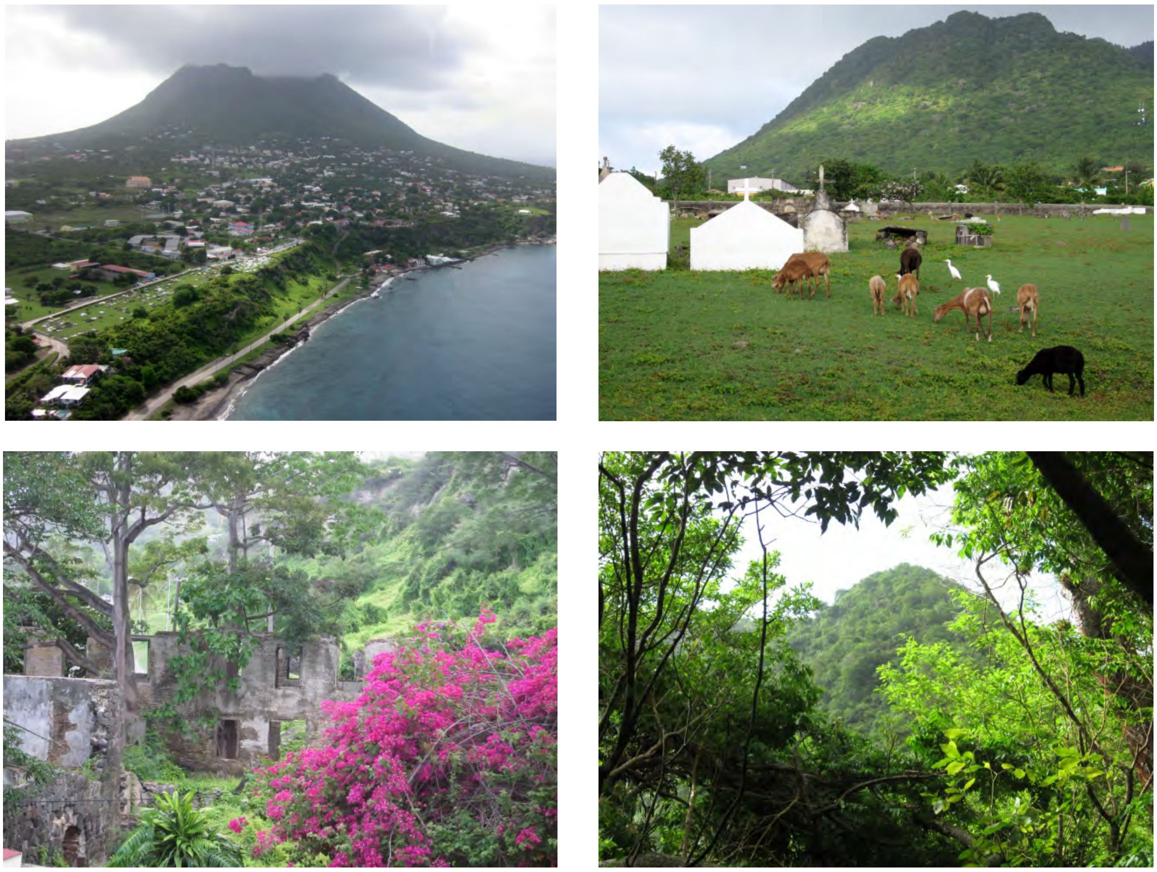

Photo 1a, b, c, d *Views on the island St Eustatius (Source photos Peter Verweij)*

The island has two volcanos, a denuded volcano in the northwest and a dormant volcano, The Quill, in the southeast (Collier & Brown, 2006). The highest point of St Eustatius is 600 m above sea level and found on The Quill (STENAPA, 2012). The island is surrounded by relatively shallow bank waters and the coasts of the island are dominated by steep cliffs, while sandy beaches are rare (Debrot & Sybesma, 2000).

The next figure shows a preliminary land cover map recently made by Alterra in collaboration with IMARES (Wageningen UR) and indicates that the major land cover types are: Thorn scrub (34%), semi-evergreen broadleaved forest (32.3%), pastures (7.45), rocks (6.4%). Only 5% of the land is related to artificial surfaces (e.g. urban areas and roads). Interesting to see is also that small areas are covered by invasive species such as Corallita (Smith et al. 2013). The land cover map can be downloaded freely from: http://www.dcbd.nl/maps.

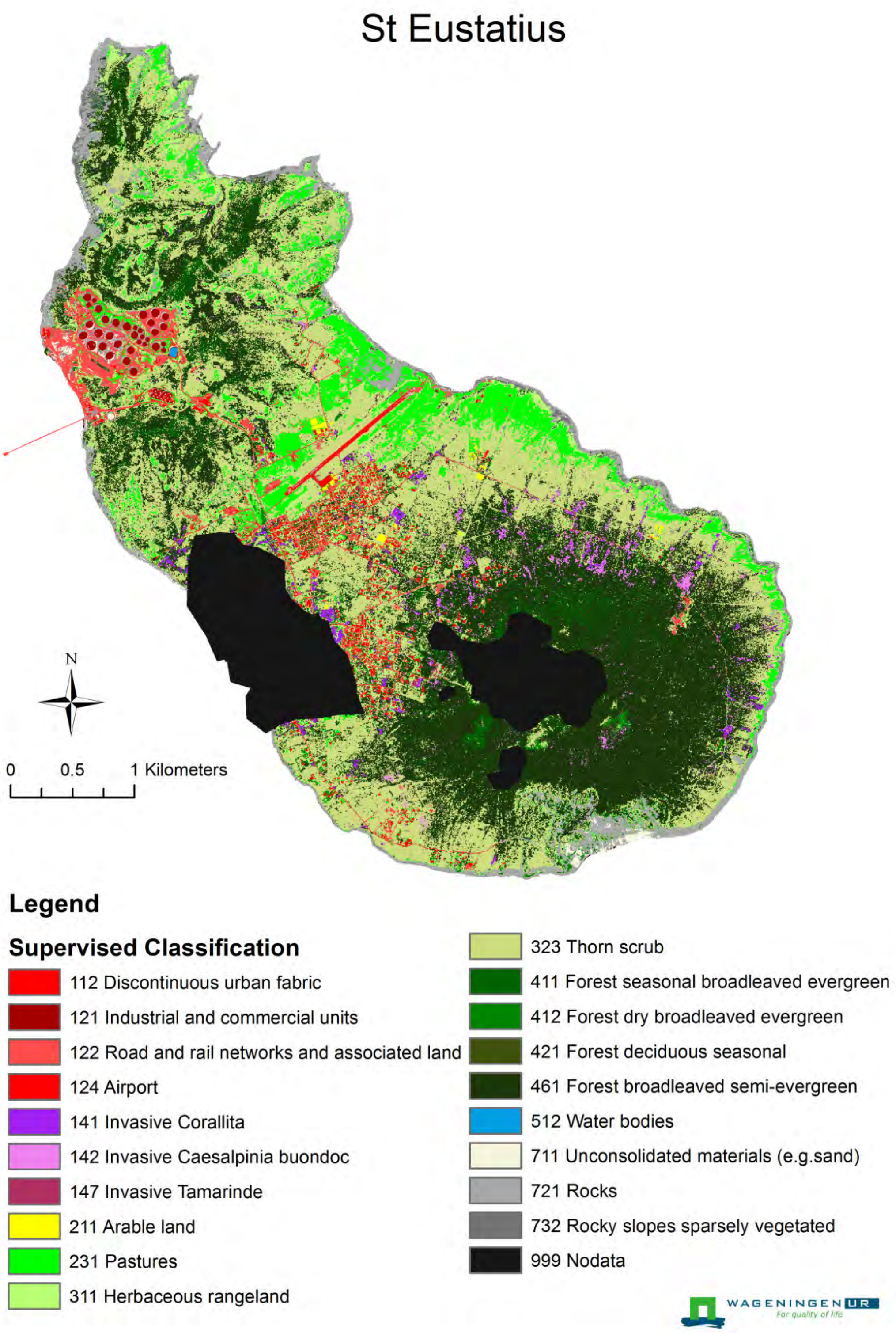

Figure 2 *Preliminary land cover map of St Eustatius, downloadable from http://www.dcbd.nl/maps*

1.2.2 Saba

Saba is the smallest of the three Dutch Caribbean islands, with a total area of 13 km^2. Saba belongs as well to the Leeward islands and is also a volcanic island. Saba is situated between 17°36' and 17°39' N latitude and between 63°15' and 63°12'W longitude. The island lies approximately 21 km northwest of St Eustatius. Its tropical climate is therefore similar to that of St Eustatius. The annual mean temperature is 27°C and the average rainfall is 1667 mm (World Travel Guide, 2012). The highest point is at the potential active volcano Mount Scenery and lies at 887 meter (Debrot & Sybesma, 2000). The island is a steep dormant volcano rising from depths of 600 m extending to 870m above sea level. The shores are steep and inaccessible. The plant communities found on Saba range from Croton thickets to (secondary) rainforest and elfin woodland (Rojer, 1997b). Saba has less than 2000 inhabitants.

Photo 2a, b, c, d *View on the island Saba (Source photos Peter Verweij)*

The figure below shows a preliminary land cover map of Saba and indicates that the major land cover types are broadleaved evergreen forest (50.6%), pastures (16.6%), thorn scrub (6.1%) and bare rocks (14.7%). Only a few percentages of the land is dedicated to houses and roads. The land cover map can be downloaded freely from: http://www.dcbd.nl/maps.

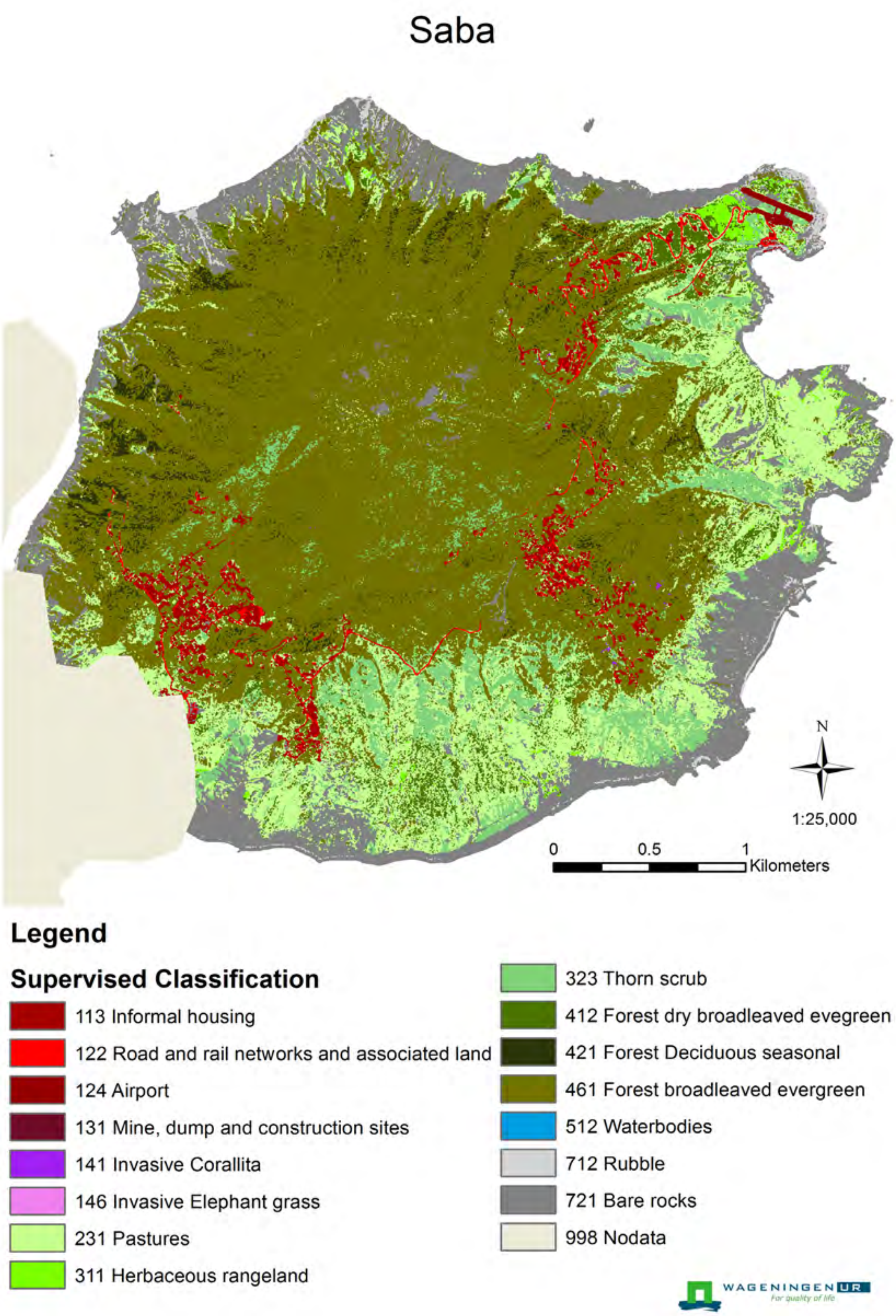

Figure 3 *Preliminary land cover map of Saba, downloadable from http://www.dcbd.nl/maps*

2 Materials

2.1 Materials

2.1.1 Aerial photographs

Aerial photographs were collected, scanned and processed by Dotka Data. The aerial survey itself was done by KLM Aerocarto – ARCADIS in 1991 (copyright by Dotka Data BV – ARCADIS). A total number of 108 stereographic aerial photographs were analysed for the two islands together. Source material consisted of colour positives. This material was scanned with 1200 dpi to create images in tiff format. The average flight scale was 1:8000 with a spatial detail of approximately 20 cm. Each aerial photograph covers approximately 390 ha (2 km * 2 km), and has approximately 60% overlap with the adjacent aerial photographs.

An example of the aerial photographs for Saba and Statia is given below.

Figure 4 *Example of an aerial photograph for Saba from 11 April 1991 with a flight scale of 1:8000 and a spatial detail of approximately 20 cm. Left Figure shows entire aerial photograph and right Figure a detail of the same photograph (copyright by Dotka Data BV – ARCADIS).*

Some characteristics of the aerial photographs are given in the two boxes below.

Table 1
Meta data of some of the aerial photographs of Saba.

Historic aerial-photo specifications: Saba 1991, Scan resolution: 1200 DPI. Date imagery:
- 20 exposures on 11 April 1991
- 33 exposures on 22 December 1991

Bronmateriaal Dia Colour Positive	Omgevi Area	Invlieg-Schaal Av flightscale	Lenscone	Datum Date	Run	Fotonr_van Exp no	Breedtegraad	Lengtegraad	Fotonr_tot	Breedtegraac	Lengtegraad
Kl/dia	Saba	8000	151	11/04/1991	6	3915	17°38'33.66"N	63°13'3.73"W	3921	17°36'35.53"N	63°14'22.62"W
Kl/dia	Saba	8000	151	11/04/1991	5	3907	17°38'50.39"N	63°13'32.03"W	3912	17°37'19.23"N	63°13'2.62"W
Kl/dia	Saba	8000	151	11/04/1991	1	3895	17°38'27.72"N	63°12'56.80"W	3901	17°38'37.65"N	63°15'31.39"W
Kl/dia	Saba	8000	151	22/12/1991	1	6313	17°38'32.83"N	63°15'32.19"W	6319	17°38'25.84"N	63°12'59.16"W
Kl/dia	Saba	8000	151	22/12/1991	2	6279	17°38'2.98"N	63°13'27.47"W	6284	17°38'11.43"N	63°15'18.53"W
Kl/dia	Saba	8000	151	22/12/1991	3	6288	17°37'38.77"N	63°15'30.62"W	6293	17°37'33.22"N	63°13'9.01"W
Kl/dia	Saba	8000	151	22/12/1991	4	6305	17°37'8.47"N	63°13'21.94"W	6311	17°37'15.88"N	63°15'46.54"W
Kl/dia	Saba	8000	151	22/12/1991	7	6297	17°37'7.95"N	63°15'25.08"W	6303	17°38'56.94"N	63°14'47.12"W

Table 2
Meta data of some of the aerial photographs of Statia.

Historic aerial-photo specifications: Sint Eustatius 1991. Scan resolution: 1200 DPI. Date imagery:

- 31 exposures on 11 April 1991
- 03 exposures on 12 April 1991
- 11 exposures on 25 March 1991
- 10 exposures on 26 March 1991

Bronmateriaal Dia Colour Positive	Omgevi Area	Invlieg-Schaal Av flightscale	Lenscone	Datum Date	Run	Fotonr_van Exp no	Breedtegraad	Lengtegraad	Fotonr_tot	Breedtegraac	Lengtegraad
Kl/dia	St Eustat	8000	151	11/04/1991	1	3862	17°30'47.63"N	63° 0'12.43"W	3866	17°31'7.31"N	62°58'48.32"W
Kl/dia	St Eustat	8000	151	25/03/1991	2	3237	17°30'14.59"N	63° 0'36.35"W	3246	17°30'1.38"N	62°57'20.20"W
Kl/dia	St Eustat	8000	151	12/04/1991	3	4135	17°29'21.80"N	63° 0'11.22"W	4142	17°29'30.02"N	62°56'46.74"W
Kl/dia	St Eustat	8000	151	25/03/1991	4	3228	17°28'39.48"N	62°59'22.87"W	3236	17°28'48.82"N	62°56'34.40"W
Kl/dia	St Eustat	8000	151	25/03/1991	5	3247	17°28'2.69"N	62°59'3.69"W	3253	17°27'56.21"N	62°57'1.47"W
Kl/dia	St Eustat	8000	151	11/04/1991	6	4040	17°31'24.98"N	63° 0'16.02"W	4047	17°29'16.16"N	62°58'15.74"W
Kl/dia	St Eustat	8000	151	11/04/1991	7	4056	17°30'15.96"N	62°58'59.99"W	4063	17°28'32.37"N	62°56'31.47"W
Kl/dia	St Eustat	8000	151	11/04/1991	8	4064	17°29'58.88"N	62°57'14.74"W	4069	17°27'55.02"N	62°57'4.99"W
Kl/dia	St Eustat	8000	151	11/04/1991	9	4079	17°30'14.50"N	62°59'49.94"W	4087	17°27'26.61"N	62°58'2.33"W
Kl/dia	St Eustat	8000	151	26/03/1991	10	3301	17°31'45.13"N	62°59'52.63"W	3307	17°28'57.79"N	62°59'47.77"W

For the georeferencing of the aerial photographs very high resolution satellite imagery was used with a 50 cm spatial resolution, see next section.

2.1.2 Reference materials

2.1.2.1 Satellite imagery
For both Saba and St Eustatius satellite imagery with a maximum spatial resolution of 50 cm were available from the Worldview-2 satellite sensor. Both the multi-spectral and panchromatic images were available. The image for Saba was acquired on 03 December 2010 and the image for St Eustatius on 18 February 2011 (Table 3). Example images are shown in Figure 5 and 6.

Table 3
Satellite imagery specifications

Sensor	Area	Resolution	Acquisition data	Max angle	Sun elevation
WorldView-2	Saba	0.5 m (pan) 2 m (ms)	03/12/2010	8.22	48.09
WorldView-2	St Eustatius	0.5 m (pan) 2 m (ms)	18/02/2011	0.42	55.14

Figure 5 *Detail of 0.5m resolution Panchromatic Worldview-2 satellite image for St Eustatius*

Figure 6 *Detail of 2m resolution Multispectral Worldview-2 satellite image for St Eustatius*

2.1.2.2 Ground Reference Control Points

In May 2013 our colleague Peter Verweij visited Saba and St Eustatius for another project and obtained from Kadaster (Netherlands' Cadastre, Land Registry and Mapping Agency) 25 ground control points for St Eustatius. These points were land marks as shown in the picture below. Unfortunately, the reference points could not be identified on the aerial photographs from 1991. Although it is assumed that these landmarks were already there in 1991, the 20 cm detail of the aerial photographs was probably not detailed enough to recognize these land marks. Therefore these reference points could not be included in the absolute calibration process. The points could only be used in the validation process of the DTM.

Photo 3 *Example of a ground control point for which x, y, z co-ordinates were available (Photo Peter Verweij)*

Erik Meesters (IMARES) provided gps tracks that were obtained from both islands. Unfortunately these tracks were not accurate enough in height measurements to be as useful as could be expected from normal gps gear (deviations in heights for more than 20 meter between the same tracks but on different days).

2.1.2.3 Projection

Every geo-referenced map or database is displayed or described in a specific projection. The project projection parameters are given mentioned below.
Projection UTM zone 20 N (WGS 1984)

PROJCS	[WGS_1984_UTM_Zone_20N]
GEOGCS	[GCS_WGS_1984]
DATUM	[D_WGS_1984]
SPHEROID	[WGS_1984,6378137.0,298.257223563]
PRIMEM	[Greenwich,0.0]
UNIT	[Degree,0.0174532925199433]
PROJECTION	[Transverse_Mercator]
PARAMETER	[‘False_Easting’,500000.0]
PARAMETER	[‘False_Northing’,0.0]
PARAMETER	[‘Central_Meridian’,63.0]
PARAMETER	[‘Scale_Factor’,0.9996]
PARAMETER	[‘Latitude_Of_Origin’,0.0]
UNIT	[‘Meter’,1.0]

2.1.3 Software

ERDAS IMAGINE & LPS

ERDAS Imagine 2013 is a software package from Intergraph for geospatial image processing, analysis and classifications. Between the many options, also profile viewing of point clouds (2D and 3D) can be realized, as shown in the Figure below.

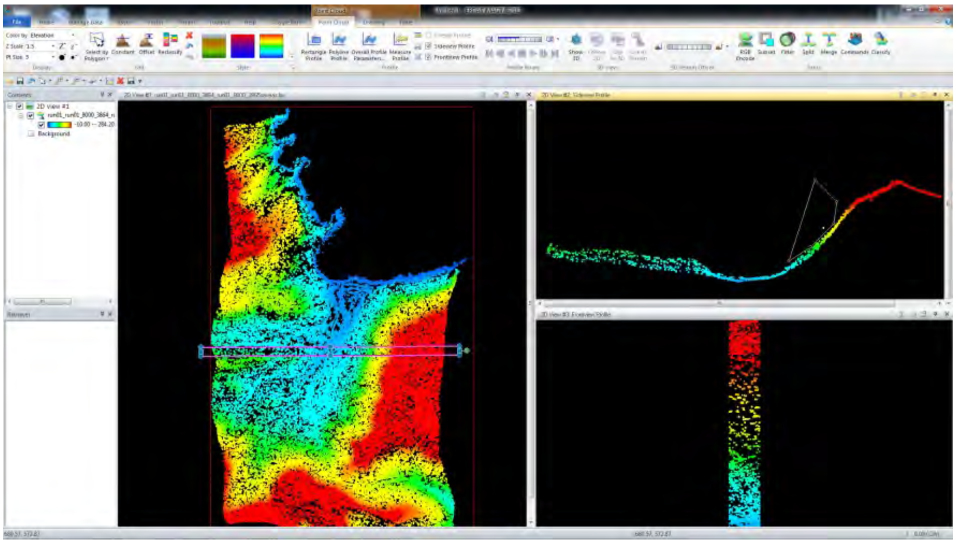

Figure 7 *Print screen of the ERDAS imagine software showing analysis of 3D point cloud las files*

ERDAS LPS is another software package used in this project for photogrammetry. The photogrammetry system delivers full analytical triangulation, next to amongst others: the generation of digital terrain models, orthophoto production, mosaicking, and 3D feature extraction. LPS is tightly integrated with ERDAS IMAGINE.

ESRI ARCGIS

While ERDAS LPS has been used for the analytical triangulation and the creation of 3d point clouds, ArcGIS 10.1 has been used for the creation of the Digital Terrain Models by sewing amongst others the Topo_to_Raster tool for the interpolation of the 3d point data to a grid. ARCSCENE 10.1 has been used for the 3D visualisation of the point clouds and interpolated DTM.

3 Methods

3.1 Photogrammetric triangulation

The aerial photographs have been georeferenced in ERDAS IMAGINE with some help of the georeferenced Worldview-2 satellite imagery. The panchromatic Worldview-2 imagery had a 50 cm spatial detail and was the most detailed reference material that was available.
To make an orthophoto, two different accuracies must be taken into account, firstly the potential accuracy of the applied materials and measuring equipment/software and secondly the required accuracy to make an orthophoto. It can be stated that the theoretical positional accuracy of a photogrammetric triangulation can be calculated according to a percentage of the flying height. The flying height can be calculated using the average photo scale * the lens cone or also referred to as focal length of the camera. In this case, the theoretical flying height is 8000 * 0.150 m = 1200 m (in reality around 1500 meters). A standard photogrammetric rule of thumb states the maximum accuracy is 1 to 2 times the pixel size, giving the 20cm resolution. The maximum potential measuring accuracy in height is 2 to 3 times more than the x,y accuracy, in this case 60 cm. The required accuracy in this case is defined in many photogrammetric manuals as 0.5 percent of the flying height, in this case 1200m * 0.005 = 6 m. The accuracy of the applied materials and measuring equipment and software of 60 cm falls well within this requirement. These georeferencing accuracy requirements can be reached by the used method.
The accuracy of the georeferencing of the aerial photographs was excellent in the end, see the triangulation summary below, and was around 0.5 pixel.

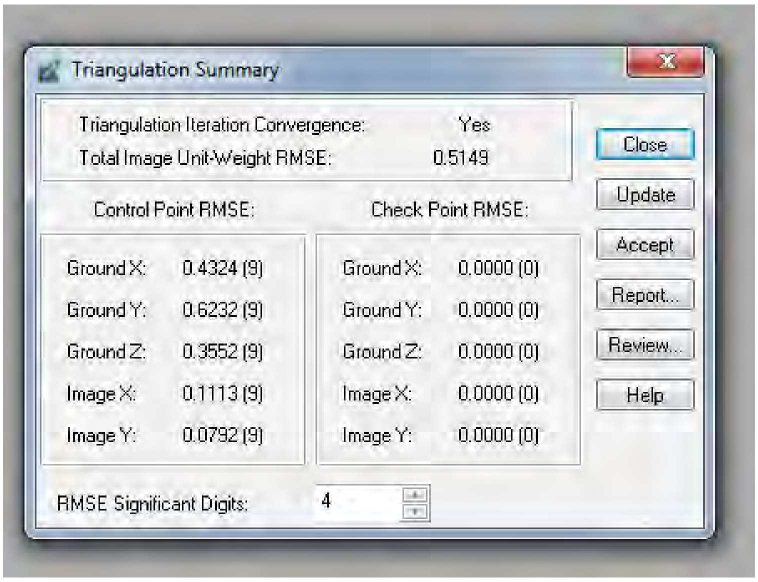

Figure 8 *Triangulation summary.*

3.2 Triangulation software

ERDAS LPS software has been used for the triangulation of the stereographic aerial photographs to create 3D point clouds as las files. Below some of the LPS block properties are mentioned that have been used in the triangulation.

Table 4
LPS Block properties.

Projection type:	UTM
Spheroid Name:	WGS84
EPSG:	32620
Average input flying height:	1500 m
Advanced Options AT:	Ebners orthogonal model

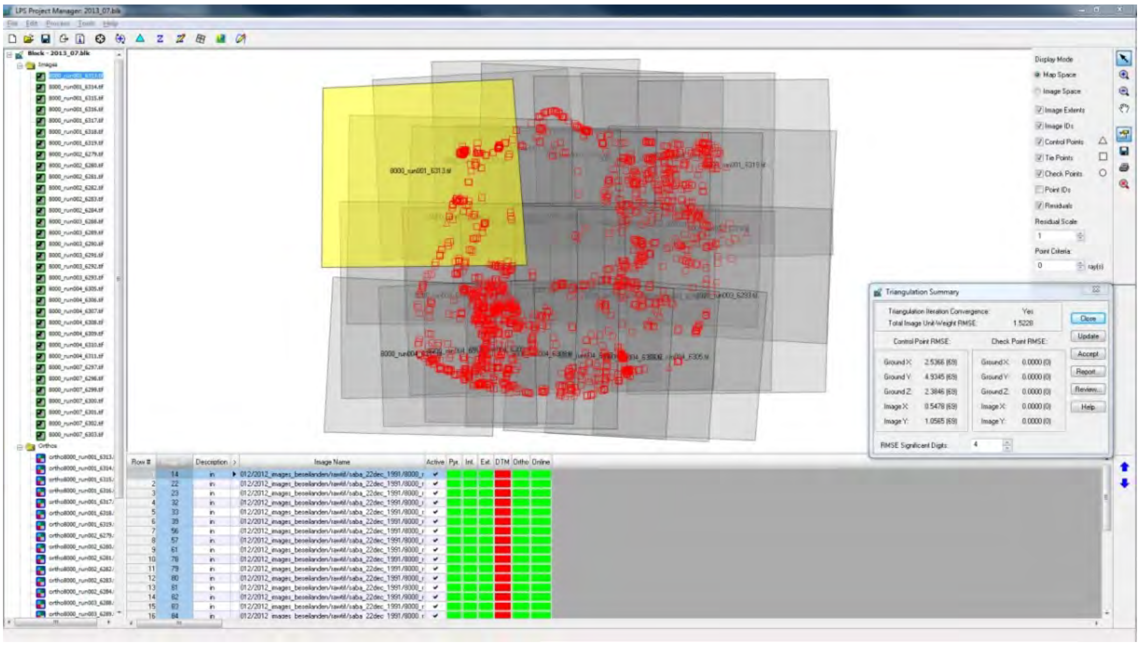

Figure 9 *Screenshot of the LPS-Project Manager and the triangulation summary for Saba (with 53 aerial photographs).*

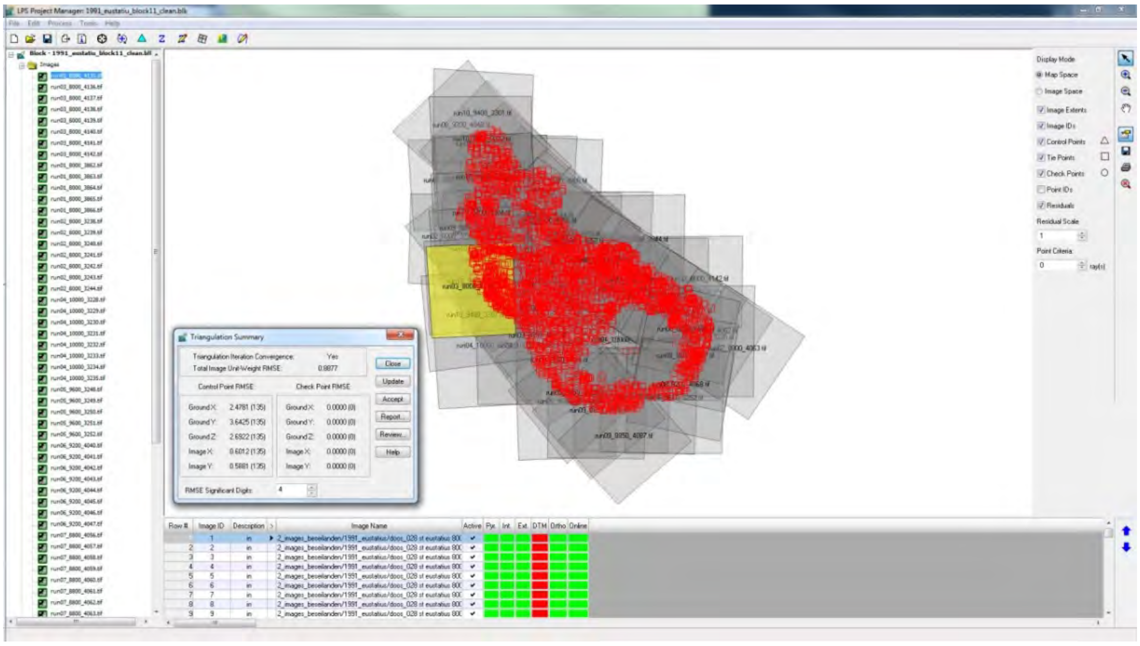

Figure 10 *Screenshot of the LPS-Project Manager and the triangulation summary for St Eustatius (with 55 aerial photographs).*

Since no ground control points were available to support the triangulation, use has been made of the coastline which can be considered to be at sea level.

3.2.1 From aerial photographs to point clouds

LPS eATE which has been used is an LPS add-on that generates RGB-encoded, dense point clouds by correlating points from stereo image pairs. LPS eATE handles data from satellite and airborne sensors, and enables one to simultaneously produce different output formats of varying density, including LAS point clouds, TINs, and GRIDs. A variety of parameter settings were tested to get the best results for every overlap. The Figure below shows the main settings that were used for SABA and St Eustatius.

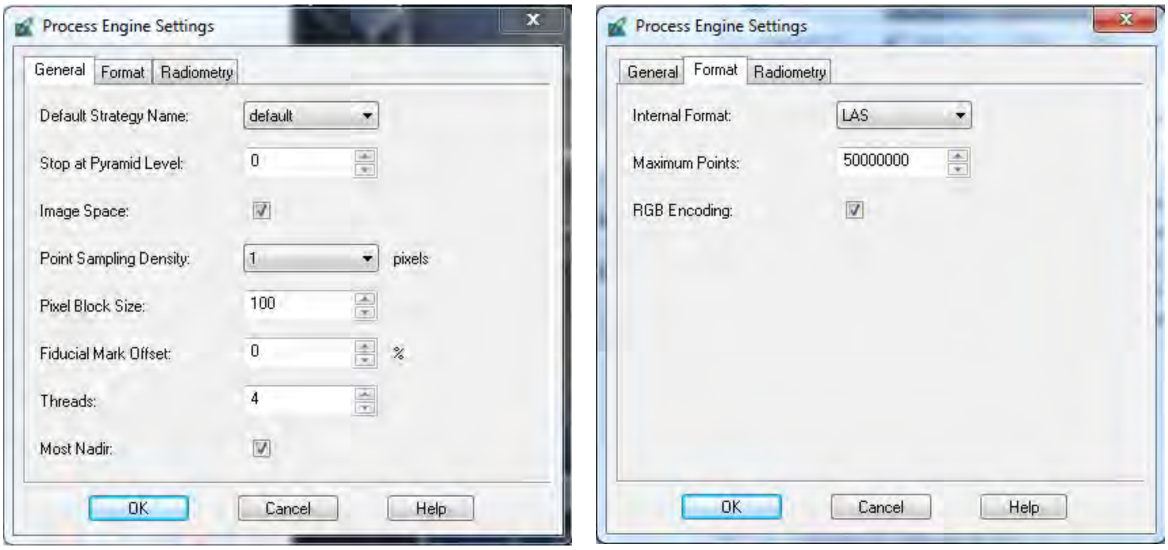

Figure 11 *LPS eATE: Process Engine Settings: General and Format settings.*

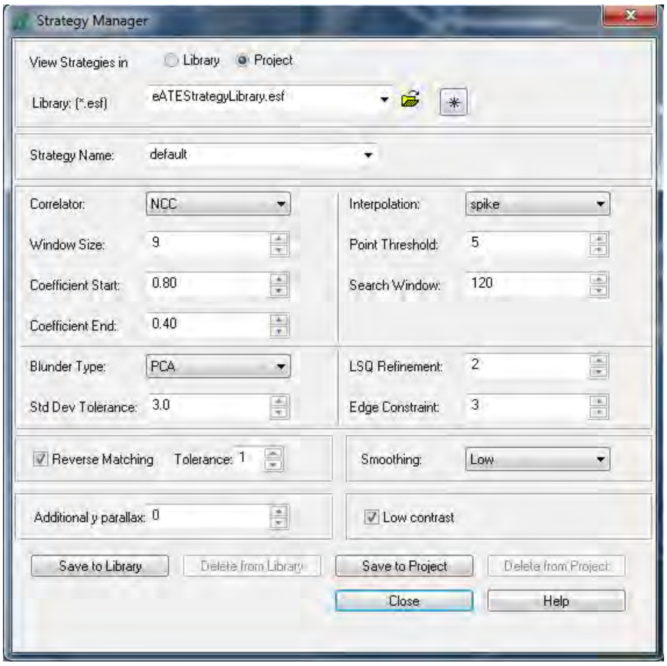

Figure 12 *Parameter setting LPS eATE Strategy manager.*

The output point cloud files were las files of approximately 1 GB in size each for Saba and Statia.

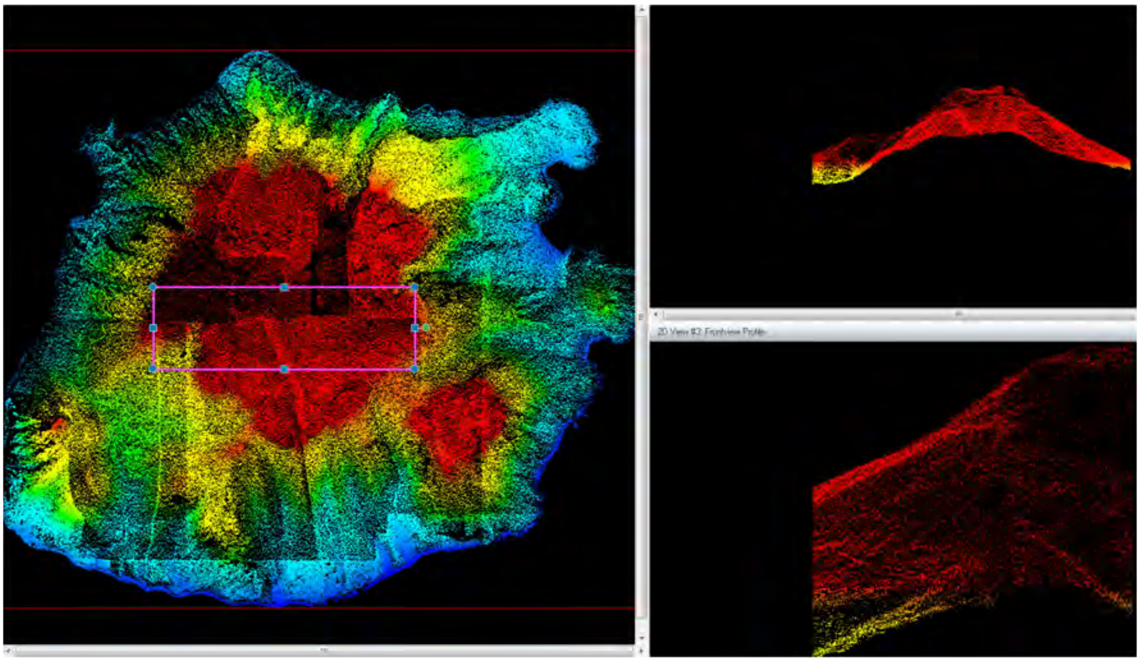

Figure 13 *Visualisation of a las file for Saba as 3d point cloud data.*

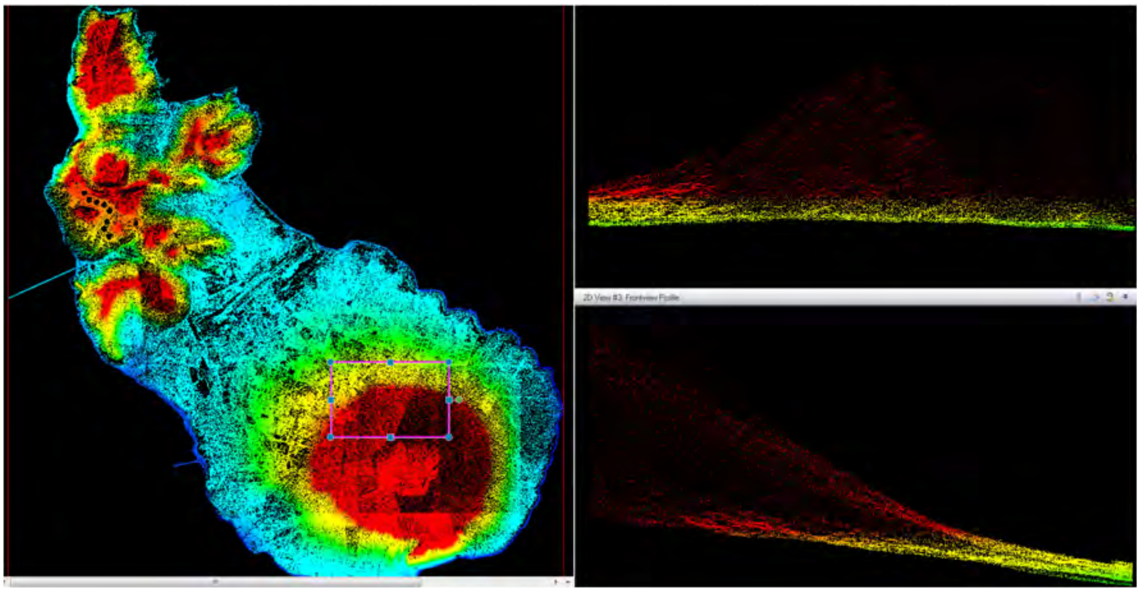

Figure 14 *Visualisation of a Las file for Statia as 3d point cloud data.*

The point clouds have been delivered to Alterra by Dotka Data in such a way that as much influence from buildings and vegetation had been removed already. This facilitated the construction of the DTMs by Alterra.

3.3 From point clouds to the DTM

3.3.1 Introduction to the interpolation method

The production of the Digital Terrain Models (DTMs) from the point cloud Las files has been done in ArcGIS 10.1 using the Topo-to-Raster tool. The Topo-to-Raster tool is an interpolation method specifically designed for the creation of hydrological correct digital terrain models (DTMs). It is based on the ANUDEM program developed by Michael Hutchinson (1988, 1989, 1996, 2000, 2011). See

Hutchinson and Dowling (1991) and ANU Fenner School of Environment and Society and Geoscience Australia (2008) for applications of ANUDEM to continent-wide DTM production. Applications of DTMs to environmental modelling are discussed in Hutchinson and Gallant (2000) and Hutchinson (2008). Further developments of ANUDEM are discussed in Hutchinson et al. (2009, 2011). Topo-to-Raster interpolates elevation values for a raster while imposing constraints that ensure:

- A connected drainage structure and
- Correct representation of ridges and streams from input contour data.

The interpolation procedure has been designed to take advantage of the types of input data commonly available and the known characteristics of elevation surfaces. This method uses an iterative finite difference interpolation technique. It is optimized to have the computational efficiency of local interpolation methods, such as inverse distance weighted (IDW) interpolation, without losing the surface continuity of global interpolation methods, such as Kriging and Spline. It is essentially a discretized thin plate spline technique (Wahba, 1990) for which the roughness penalty has been modified to allow the fitted DTM to follow abrupt changes in terrain, such as streams, ridges and cliffs. The program acts conservatively in removing sinks and will not impose the drainage conditions in locations that would contradict the input elevation data. Such locations normally appear in the diagnostic file as sinks. This information is used to correct data errors, and is particularly needed when processing large datasets (ESRI ARCGIS). For more details see also ESRI ARCGIS documentation.

3.4 Seamless DTM production

The Las data files used to create a DTM for both Saba and St Eustatius contains tens of millions of points. Before being able to compute the DTM's, pre-processing is required. The main pre-processing steps involved to create the DTM are:

1. Convert the point clouds into point features with a z-coordinate. The Topo-to-Raster Tool does not facilitate Las file formats as an input for the ArcGIS 10.1 version used.
2. Each Las file has tens of millions of points and as a result creates an enormous point feature dataset in ArcGIS. Therefore, it is essential to create a spatial index to handle these data for both computations and presentations.
3. It is necessary to change the default values for specific parameters of the Topo-to-Raster tool in ArcGIS; these are roughness_penalty, discrete_error_factor, vertical_standard_error and a specific tolerance.
4. Carry out a visual check to detect possible major artefacts in the DTM.
5. After the DTM's have been created, the sea area needs to be removed from the DTM and replaced by a mean sea level value. This area represents the extrapolated area of the computation.

The software package FME was used to convert the point cloud Las file data into point features with height coordinates. The point features were saved in a file geodatabase. This is necessary to manage the tens of millions of points generated by the conversion. The choice of point feature format is crucial in this case. It is necessary to use the internal database management facilities to handle such large datasets as in this case. Otherwise long pauses in computing and visualizing are bound to happen. Shape files cannot facilitate this need.

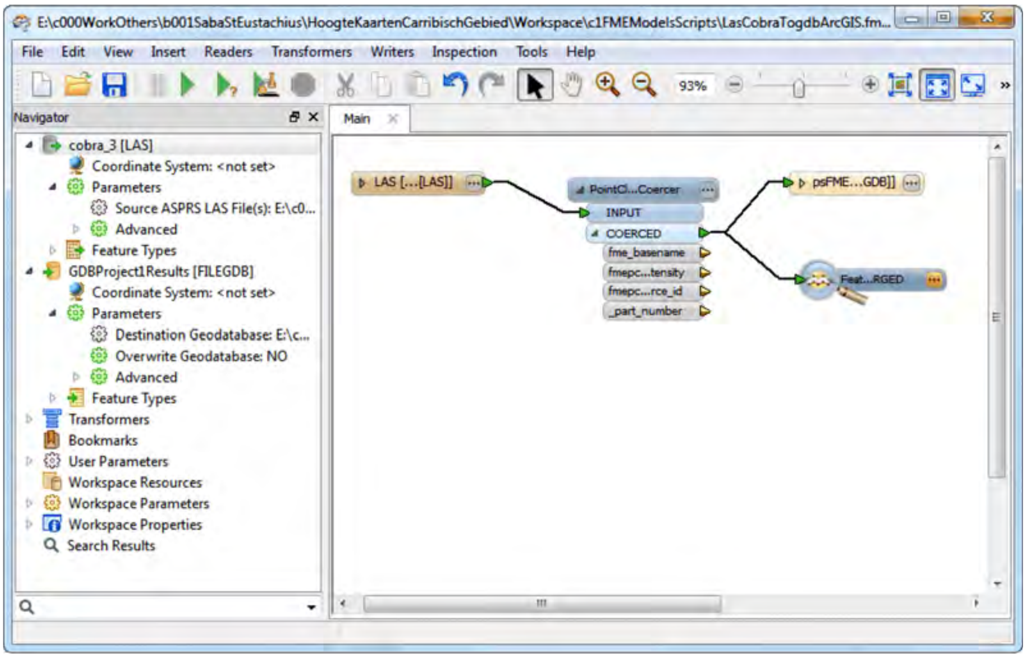

Figure 15 *Workflow in FME to concert the Las file data into point features with height co-ordinates.*

To spatially index the point feature datasets the tool Add Spatial Index was used in ArcGIS. The following spatial index values were used:

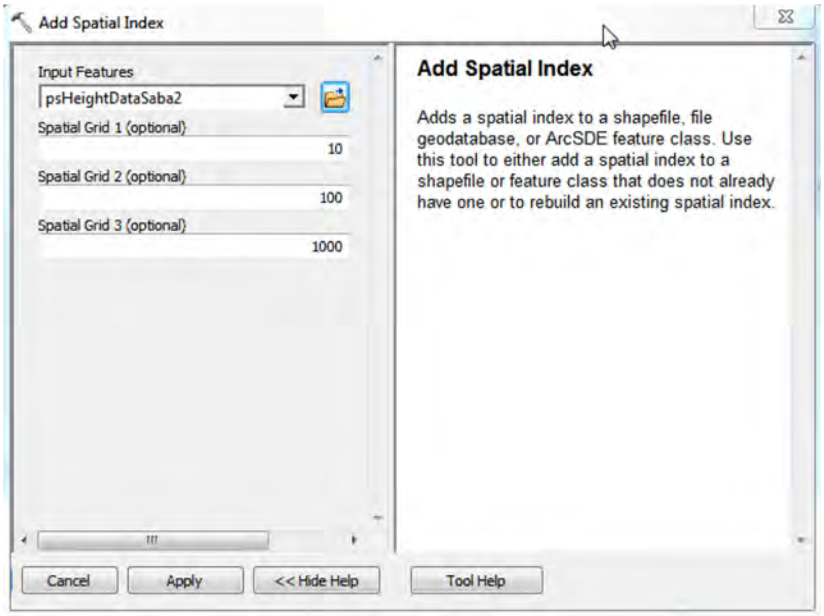

Figure 16 *SpatialIndexValues.*

Note this computation can take quite some time; in this case 12 and 17 minutes. However, skipping this computation will lead to far greater time loss in the remaining computations.
To calculate the DTM with Topo-to-Raster, it is necessary to adjust the default parameters. The parameters roughness_penalty, discrete_error_factor, vertical_standard_error and tolernance 2 need to be altered. These have a direct effect on the computation and the calculated results. The default settings are set for contour lines as being the main height input. In this case, the main inputs are height points: also referred to as spot heights. The following parameters in the Topo-to-Raster tool were changed to fit this condition:

1. Primary type of input data :Spot
2. Roughness penalty :0.5
3. Profile curvature roughness penalty :0.5
4. Discrete error factor :2
5. Tolerance 2 :200

The purpose of these parameters is described in the following table: (table content is coming from ArcGIS 10.1 help):

Table 5
Overview of parameters

roughness_penalty (Optional)	The integrated squared second derivative as a measure of roughness. The roughness penalty must be zero or greater. If the primary input data type is CONTOUR, the default is zero. If the primary data type is SPOT, the default is 0.5. Larger values are not normally recommended.
discrete_error_factor (Optional)	The discrete error factor is used to adjust the amount of smoothing when converting the input data to a raster. The value must be greater than zero. The normal range of adjustment is 0.5 to 2, and the default is 1. A smaller value results in less data smoothing; a larger value causes greater smoothing.
vertical_standard_error (Optional)	The amount of random error in the z-values of the input data. The value must be zero or greater. The default is zero. The vertical standard error may be set to a small positive value if the data has significant random (non-systematic) vertical errors with uniform variance. In this case, set the vertical standard error to the standard deviation of these errors. For most elevation datasets, the vertical error should be set to zero, but it may be set to a small positive value to stabilize convergence when rasterizing point data with stream line data.
tolerance_2 (Optional)	This tolerance prevents drainage clearance through unrealistically high barriers. The value must be greater than zero. The default is 100 if the data type is CONTOUR and 200 if the data type is SPOT.

It is essential to check the DTM after computation for possible errors. Irregularities, so called artefacts, can occur due to errors in the original height data. By calculating the slope, areas with an illogical steepness can give an indication where sharp inclinations of the surface are. When these inclinations are not conform to the expected surface shape, it is an indication that the input data was incorrect.

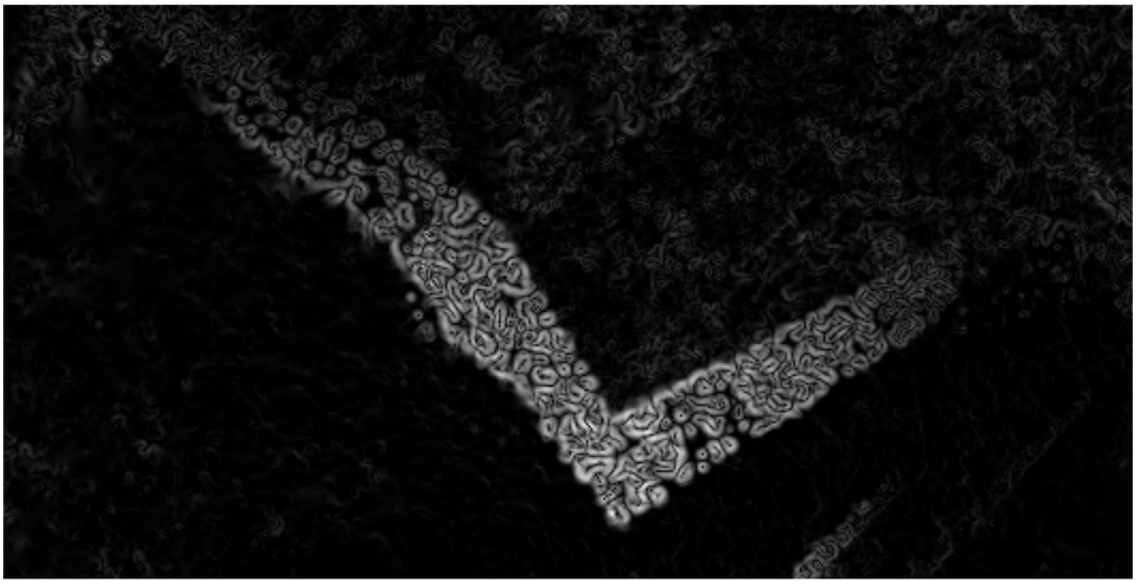

Figure 17 *Image with slopes as an example to detect errors as shown above in the DTM.*

By visualizing the slope and looking at the height difference, these types of artefacts can be detected. Re-computation of the height for these areas is then required.

The Topo-to-Raster function interpolates between the given height data. Areas outside the given points will be extrapolated in the calculation, but are being calculated incorrectly. They must be excluded or substituted by other data. An example of an extrapolated error result is in the following Figure:

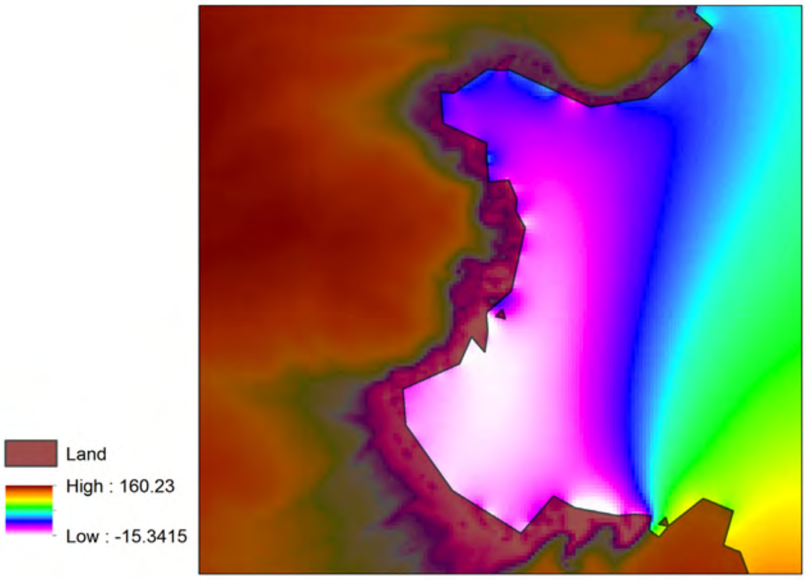

Figure 18 *Image with extrapolated errors in DTM.*

The left-side of this Figure shows the land area where the interpolation calculation is correct. The right-side shows the extrapolated sea area with errors since it should be flat. Therefore the sea area needs to be masked. In this case the sea area was substituted with the value zero. After these computations DTMs had been created that was suitable for the production of the orthophotos.

3.5 Production of Ortho-mosaics

An orthophoto, orthophotograph or ortho-image is an aerial photograph geometrically corrected - 'orthorectified' - in such a way that the scale is uniform (source: Wikipedia). This means that the orthophoto has no distortions in distance anymore and can be used to produce for example topographic maps. Unlike an uncorrected aerial photograph, an orthophotograph can be used to measure true distances, because it is an accurate representation of the Earth's surface, being adjusted for amongst others topographic relief, lens distortion, and camera tilt.

DTMs made by Alterra were delivered again to Dotka Data to produce ortho-mosaics of the aerial photographs. This was done again with the use of the software LPS-eAte of Intergraph. LPS enables you to perform powerful yet simple orientation and ortho-rectification. It provides all of the necessary tools required to transform raw imagery into reliable geospatial data. This comprehensive product includes amongst others: i) photogrammetric project setup and management, ii) support for numerous sensor models, iii) automatic interior orientation, iv) manual and automatic point measurement, v) triangulation and ortho-rectification, and vi) terrain preparation and conversion.

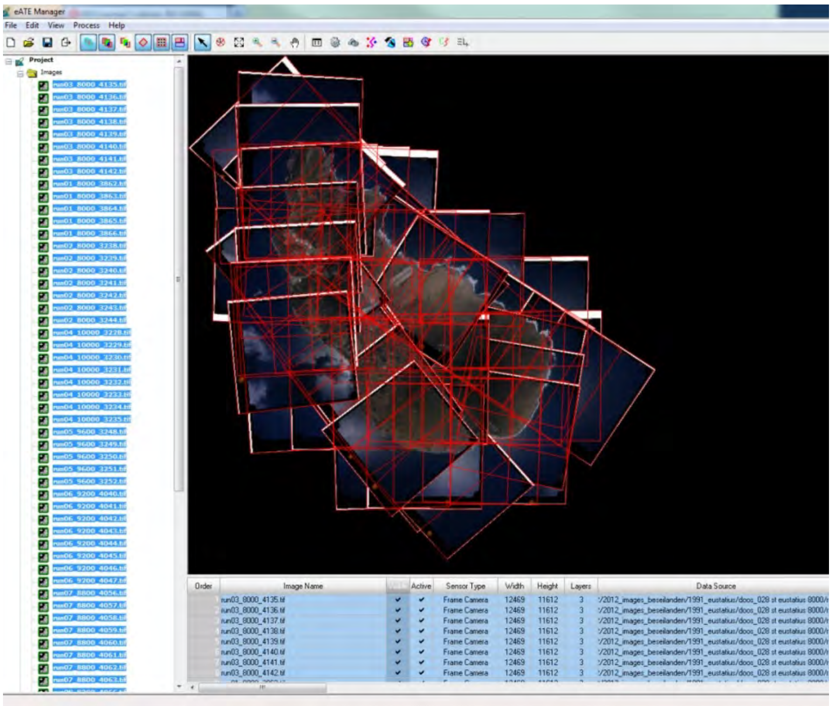

Figure 19 *Example of the LPS eAte interface that was used to create the orthophotos with the help of the produced DTMs.*

3.6 3D Rotation of height points St Eustatius

Due to the lack of quality ground control points, the photogrammetric triangulation depended upon many relative reference points between the aerial photographs. This generates one 3d model, however levelling this model can lead to a tilted reference surface, in this case a possible tilted coastline. This can be visually checked by manually measuring height points along the coastline of the islands. These points are expected to have zero height. In the case of Saba, the coastal height points fell within the required accuracy showing no apparent tilt. However, St Eustatius showed a definite tilt from height points that are too high along the northern coast to near sea level in the south. Figure 20 shows red circles presenting the height difference along the coast. The bigger the circle represents a higher the difference in height. The measured height differences are between 40 meters in the north to 0 meters in the south. In Figure 20 you can see a gradual change of size from north to south indicting a tilted surface. The tilt can be removed used a 3d affine transformation.

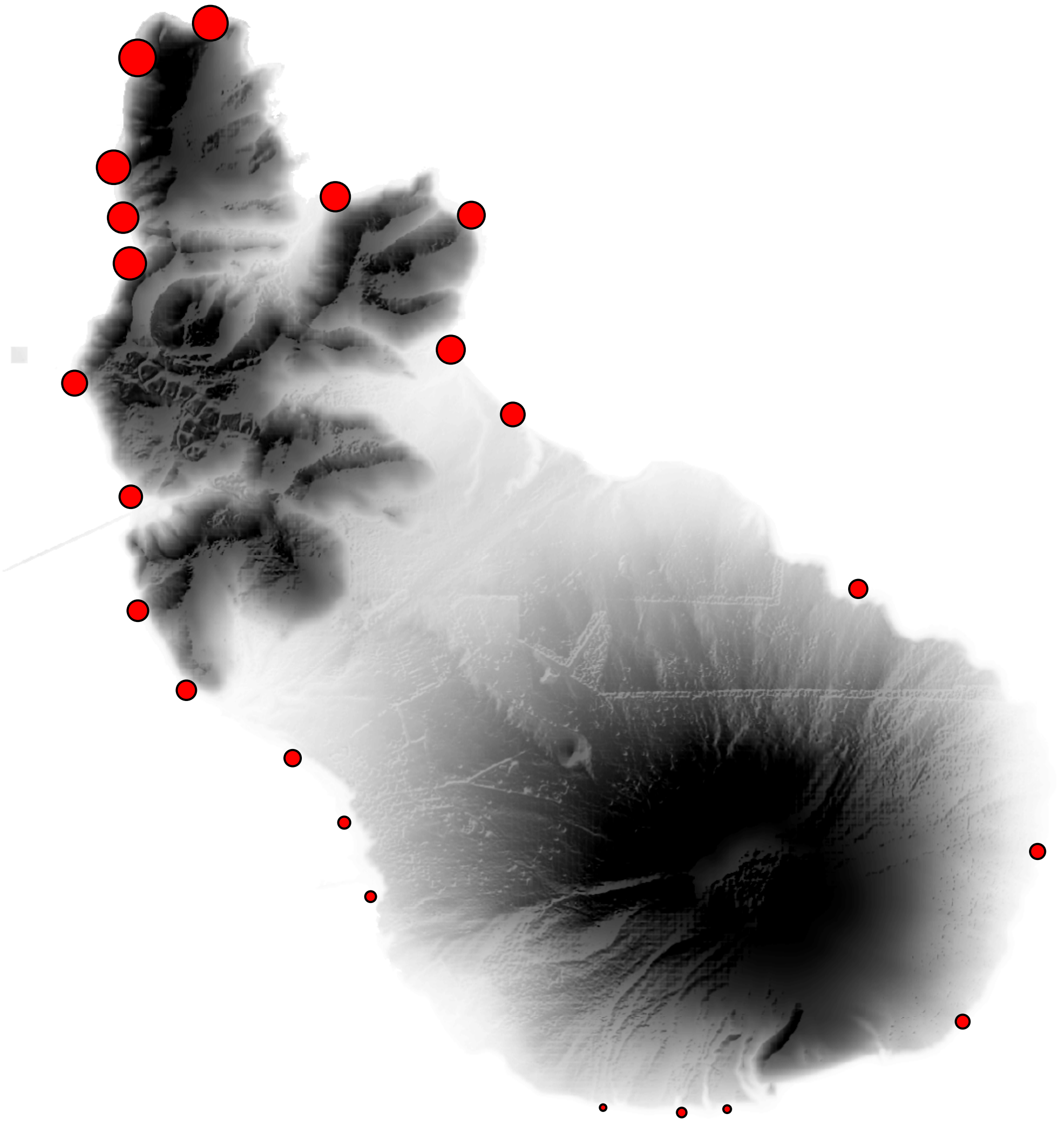

Figure 20 *DTM is give in a grey colour scale from white along the coast to black at the highest point. The size of the circles represents the height difference along the coast.*

Twenty-two new reference points were used to compute the required 3d transformation parameters. The program RiSCAN Pro from the company Riegl was used to determine the transformation parameters. The following transformation parameters were obtained:

0.999999938	-0.000001378	-0.000353182	2.698837104
0.000002714	0.999992840	0.003784140	12.451148220
0.000353175	-0.003784141	0.999992778	7131.999616055
0.000000000	0.000000000	0.000000000	1.000000000

The RMSE of this computation was less than 1 meter, well within the required accuracy. It must be stated that this result is only applicable for the given reference points. Errors in height can still be expected, especially along the coast where you have steep slopes. Small displacements in X-, Y-position will lead to bigger height differences. These parameters were applied in the 3d affine transformation computation available in FME of Safe Software Inc. The Figure below shows the workbench model for the transformation.

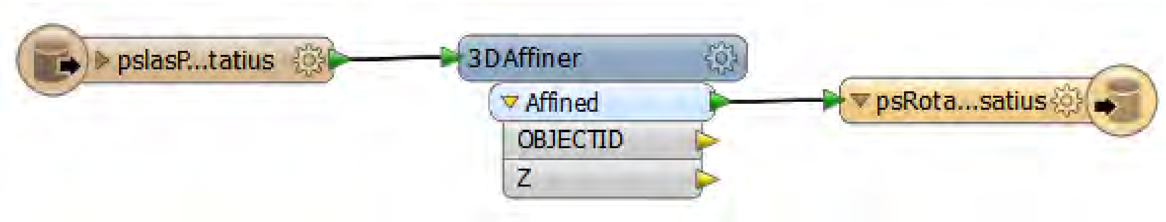

Figure 21 *Model used to transform tilted height points of St Eustatius.*

These new points are used to recalculate the final DTM of St Eustatius using the ArcGIS procedure as described in chapter 3.4 Seamless DTM Production.

4 Results

4.1 Digital Terrain Models

The resulting Digital Terrain Models (DTM) for Saba and St. Eustatius have a horizontal spatial resolution of 5 meters (x,y) with height (z) values in meters (stored as float values). The accuracy in height is approximately 60 cm (see 3.1). However, a thorough validation has not been performed. Note for example that the highest point of St Eustatius is 600 meters in the DTM while 602 meters is being mentioned on several websites. And for Saba the highest point in the DTM is 871 meters, while 887 meters is being mentioned on several websites. These kind of differences should be further investigated, and stresses once more the use of sufficient ground control points. Figure 22 shows the DTM of St. Eustatius for the whole of the island, clearly showing the hills in the north and the volcano The Quill in the south. The high spatial detail of the DTM can be seen in the north where various mountain ridges (linear lighter parts) and gullies (linear darker parts) are clearly visible. Also gullies that go downhill from the volcano can be seen clearly.

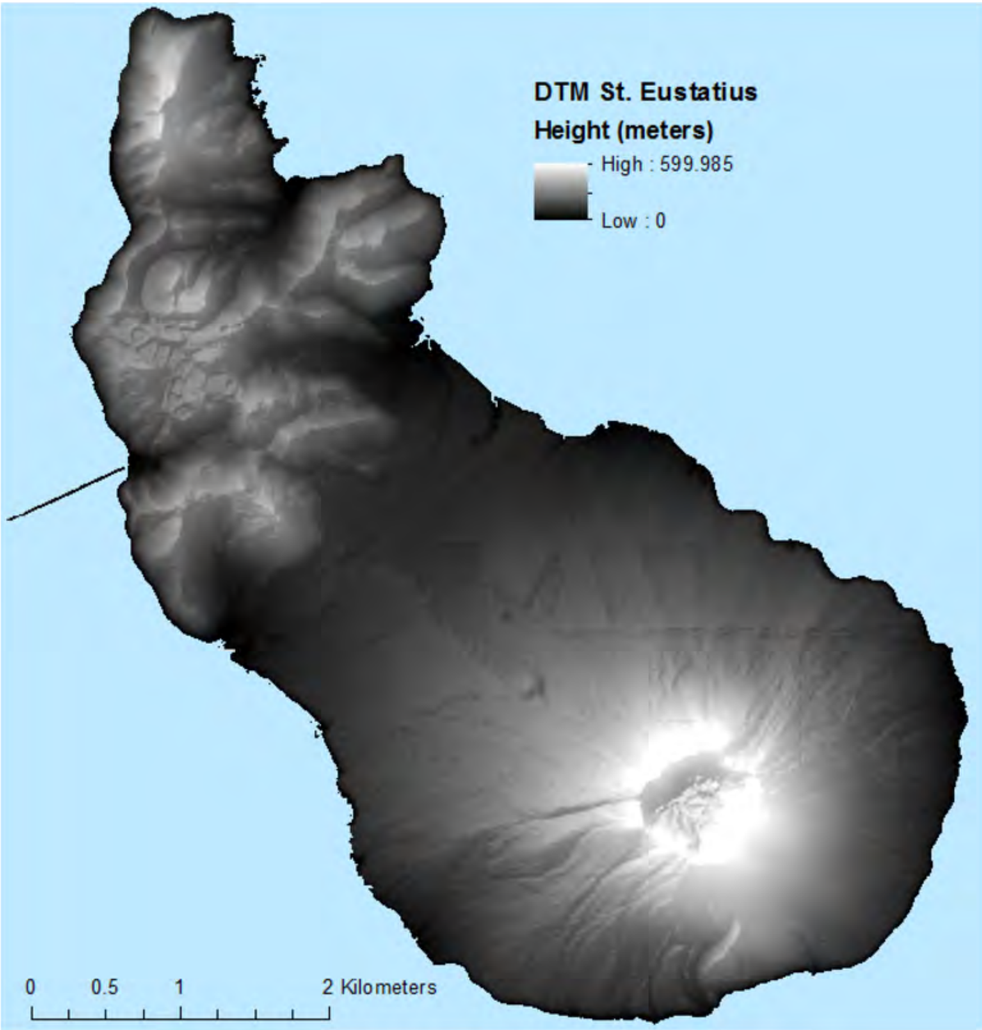

Figure 22 *Digital Terrain Model of St. Eustatius.*

The DTM of Saba is shown in Figure 23, with the volcano Mount Scenery clearly visible in the middle. The pattern of mountain ridges and gullies is also clearly visible on the DTM of Saba.

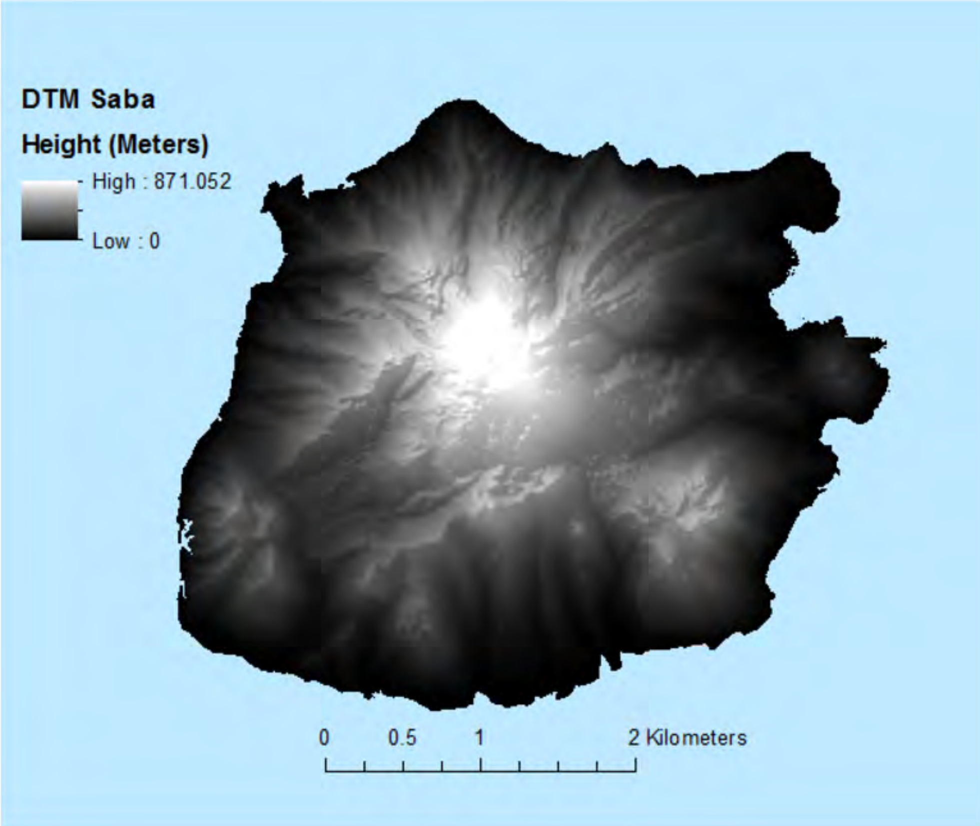

Figure 23 *Digital Terrain Model of Saba.*

4.2 Orthomosaics

Aerial photographs with a high spatial detail that cover an area of several square kilometres, like the islands of St. Eustatius and Saba, cannot be acquired in a single shot. The aerial photographs were taken by flying several strips over the island, each strip covering approximately 2 kilometres (depending on the flight height). One of the characteristics of an aerial photograph is that locations towards the edge of the photo are slightly distorted. For example, if a high building is located near the edge of the photo, then the side of the building that faces the camera will be visible and the other side of the building will not be visible at all. It looks like the building is falling away from the camera and the roof of the building will not be in the correct location, and it can easily be shifted several meters. If the building would be exactly in the middle of the photo (directly beneath the camera), then only the roof of the building would be visible and it would be in the correct location. This same distortion takes place with differences in height of the ground surface. These distortions can be corrected by using an accurate Digital Terrain Model (DTM). Based on the x,y location and its corresponding height (z) from the DTM, the correct location of every part in the aerial photo can be calculated. This is the process of ortho-rectification. The constructed ortho photos will contain the image of the island where for every part of the photo it looks like it was taken from directly above.
During this process, all different orthophotos are stitched together. The result is as ortho-mosaic, which is one photo mosiac for the whole island. Figure 24 shows the ortho-mosaic of St. Eustatius that is constructed from the available aerial photographs of 1991. The detail of the ortho-mosiac is 20 cm's.

Figure 24 *Overview and detail Orthophoto mosaic of St. Eustatius.*

Figure 25 *Overview and detail of the Orthophoto mosaic of Saba with a 20 cm detail*

4.3 3D visualisation

The available ortho-mosaics and DTM's can be used for many purposes. The DTM's can be used as source data in hydrological, meteorological or climatological analyses when surface height is a key variable. In combination with the ortho mosaics, the DTM's can be used to create detailed 3D visualisations of the islands. This can be an interactive 3D application on a pc or in a webview or it can be used to create flyby movies over the islands or 3D snapshots of places of interest.
Figure 26 shows a 3D view of St. Eustatius using the DTM with 5 m detail and the ortho-mosaic with 50 cm detail. The ortho-mosaic is resampled for performance purposes.

Figure 26 *3D view of St. Eustatius.*

Figure 27 shows a 3D view from Tumble-Down-Dick Bay into the island along the storage tank of the oil terminal that is created with using the created DTM and orthophoto from 1991. Figure 28 shows the same view as it can be created with Google Earth, showing a photo of 2013. Apart from the differences in time, the differences in detail and accuracy of the DTM show up clearly. The reproduction of the 3D terrain in the Google Earth view is much more coarse, which is clearly visible at the skyline of the hills. Also the location of the roads in the terrain is much better in Figure 27.

Figure 27 *3D view from Tumble-Down-Dick Bay with own datasets, photo 1991.*

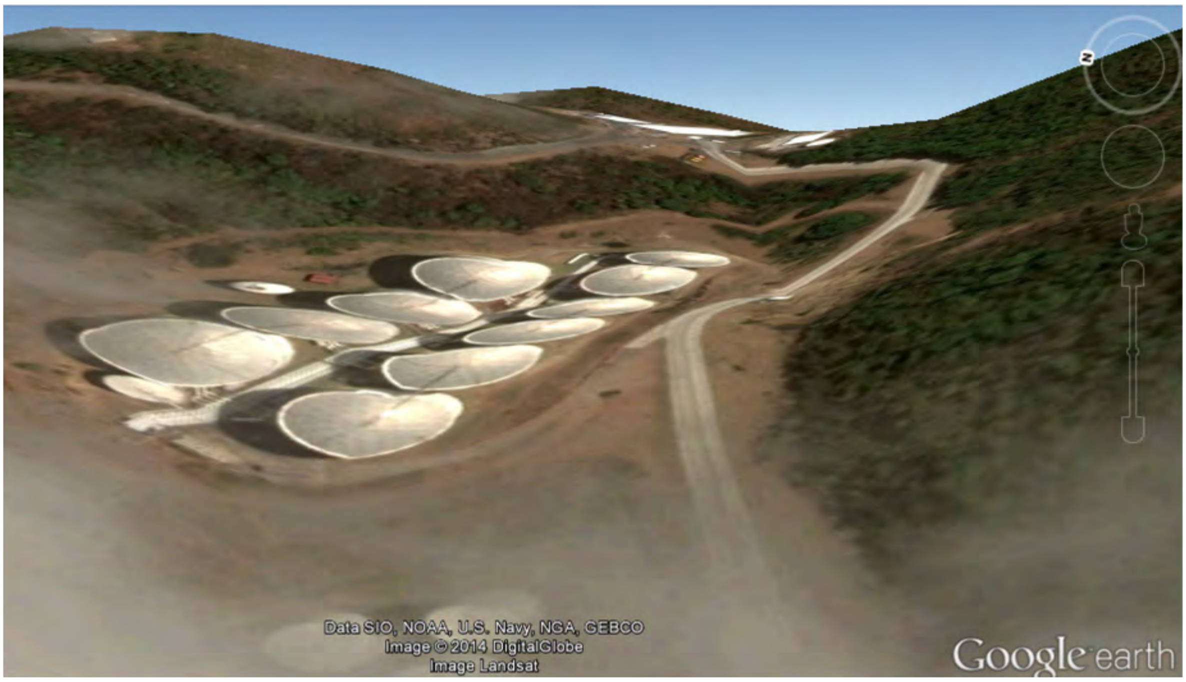

Figure 28 *3D view from Tumble-Down-Dick Bay with Google Earth, photo 2013.*

These differences in accuracy are expected; the terrain model that is used in Google Earth is based on the DTM that was created by the Shuttle Radar Topography Mission (Farr, 2007). The detail for most parts of the world for this DTM is 90 metres. Another restriction of the Google Earth dataset is that it can only be used with the Google Earth viewer. It is not possible to integrate the Google Earth data in one's own analyses.
Figure 29 show a 3D view of Saba with the airport in front.

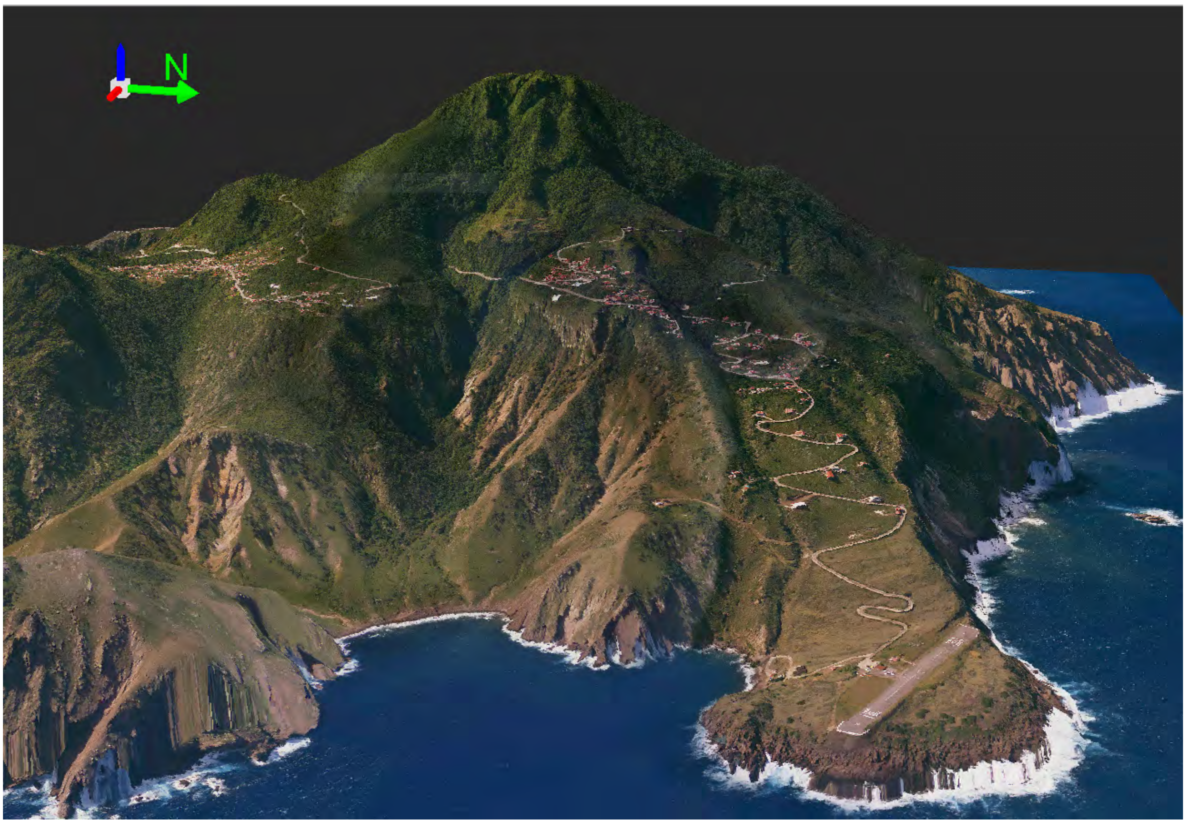

Figure 29 *3D view of Saba.*

5 Recommendations

- For geomorphological and hydrological studies the DTMs can still be improved. For this purpose additional height data needs to be used: gully locations, sink areas (inner volcano areas), cliff ridges, lake areas, etc. These data can be created by interpreting them from the existing DTM and the available orthophotos.
- Precise ground control points should be acquired for the calibration of the photogrammetric model. For this a ground survey is needed and can be quite expensive.
- A thorough validation of the produced DTMS would be recommended as well.
- In an ideal situation the DTMs should have been produced on basis of LiDAR altimeter measurements as is being used for the production of AHN (Actueel Hoogtebestand Nederland) in the Netherlands.
- A detailed DTM and ortho-mosaic should also be produced for Bonaire.

References

ANU Fenner School of Environment and Society and Geoscience Australia, 2008. GEODATA 9 Second DEM and D8 Digital Elevation Model and Flow Direction Grid, User Guide. Geoscience Australia, 43 pp. See: http://www.ga.gov.au/image_cache/GA11644.pdf.

Farr, T. G., et al. (2007), The Shuttle Radar Topography Mission, Rev. Geophys., 45, RG2004, doi:10.1029/2005RG000183.

Hutchinson, M. F. 1988. Calculation of hydrologically sound digital elevation models. Paper presented at Third International Symposium on Spatial Data Handling at Sydney, Australia.

Hutchinson, M. F. 1989. A new procedure for gridding elevation and stream line data with automatic removal of spurious pits. Journal of Hydrology, 106: 211–232.

Hutchinson, M. F., and T. I. Dowling. 1991. A continental hydrological assessment of a new grid-based digital elevation model of Australia. Hydrological Processes 5: 45–58.

Hutchinson, M. F. 1996. A locally adaptive approach to the interpolation of digital elevation models. In Proceedings, Third International Conference/Workshop on Integrating GIS and Environmental Modeling. Santa Barbara, CA: National Center for Geographic Information and Analysis. See: http://www.ncgia.ucsb.edu/conf/SANTA_FE_CD-ROM/sf_papers/hutchinson_michael_dem/local.html.

Hutchinson, M.F. 2000. Optimising the degree of data smoothing for locally adaptive finite element bivariate smoothing splines. ANZIAM Journal 42(E): C774–C796.

Hutchinson, M.F. and Gallant, J.C. 2000. Digital elevation models and representation of terrain shape. In: J.P. Wilson and J.C. Gallant (eds) Terrain Analysis. Wiley, New York, pp. 29–50.

Hutchinson, M.F. 2008. Adding the Z-dimension. In: J.P. Wilson and A.S. Fotheringham (eds), Handbook of Geographic Information Science, Blackwell, pp 144–168.

Hutchinson, M.F., Stein, J.A., Stein, J.L. and Xu, T. 2009. Locally adaptive gridding of noisy high resolution topographic data. In Anderssen, R.S., R.D. Braddock and L.T.H. Newham (eds) 18th World IMACS Congress. Modelling and Simulation Society of Australia and New Zealand and International Association for Mathematics and Computers in Simulation, July 2009, pp. 2493–2499. See: http://www.mssanz.org.au/modsim09/F13/hutchinson.pdf.

Hutchinson, M.F., Xu, T. and Stein, J.A. 2011. Recent Progress in the ANUDEM Elevation Gridding Procedure. In: Geomorphometry 2011, edited by T. Hengel, I.S. Evans, J.P. Wilson and M. Gould, pp. 19–22. Redlands, California, USA. See: http://geomorphometry.org/HutchinsonXu2011.

Smith, S.R., Mücher, C.A., Debrot, A.O., Roupioz, L., Meesters, H.W.G., Hazeu, G.W, Davaasuren, N., 2013. Use of satellite data for the monitoring of species on Saba and St. Eustatius. IMARES rapport C124/13 (BO-11-011.05-019), 86 pp.

Wahba, G. 1990. Spline models for Observational data. Paper presented at CBMS-NSF Regional Conference Series in Applied Mathematics. Philadelphia: Soc. Ind. Appl. Maths.

Alterra Wageningen UR
P.O. Box 47
6700 AA Wageningen
The Netherlands
T +31 (0)317 48 07 00
www.wageningenUR.nl/en/alterra

Alterra report 2569
ISSN 1566-7197

Alterra Wageningen UR is the research institute for our green living environment. We offer a combination of practical and scientific research in a multitude of disciplines related to the green world around us and the sustainable use of our living environment, such as flora and fauna, soil, water, the environment, geo-information and remote sensing, landscape and spatial planning, man and society.

The mission of Wageningen UR (University & Research centre) is 'To explore the potential of nature to improve the quality of life'. Within Wageningen UR, nine specialised research institutes of the DLO Foundation have joined forces with Wageningen University to help answer the most important questions in the domain of healthy food and living environment. With approximately 30 locations, 6,000 members of staff and 9,000 students, Wageningen UR is one of the leading organisations in its domain worldwide. The integral approach to problems and the cooperation between the various disciplines are at the heart of the unique Wageningen Approach.

To explore the potential of nature to improve the quality of life

Alterra Wageningen UR
P.O. Box 47
6700 AB Wageningen
The Netherlands
T +31 (0) 317 48 07 00
www.wageningenUR.nl/en/alterra

Alterra Report 2569

Alterra Wageningen UR is the research institute for our green living environment. We offer a combination of practical and scientific research in a multitude of disciplines related to the green world around us and the sustainable use of our living environment, such as flora and fauna, soil, water, the environment, geo-information and remote sensing, landscape and spatial planning, man and society.

The mission of Wageningen UR (University & Research centre) is 'To explore the potential of nature to improve the quality of life'. Within Wageningen UR, nine specialised research institutes of the DLO Foundation have joined forces with Wageningen University to help answer the most important questions in the domain of healthy food and living environment. With approximately 30 locations, 6,000 members of staff and 9,000 students, Wageningen UR is one of the leading organisations in its domain worldwide. The integral approach to problems and the cooperation between the various disciplines are at the heart of the unique Wageningen Approach.