**Geological Survey of Ireland Research Programme**
***- Short Call 2015, Final Report -***

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| Name of Lead Investigator | Conor Cahalane |
| Email | Conor.cahalane@nuim.ie |

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| Organisation name | Maynooth University | | |
| Organisation type: | ☒HEI | ☐Public Sector (other) | ☐Private Sector |
| Department/section | National Centre for Geocomputation | | |

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| Project Title | Developing a rapid, low cost bathymetric survey methodology using multi-resolution imagery |
| Contract No. | 2015-sc-024 |

# 1. Objectives and scientific/engineering targets beyond the state of the art

Calculating bathymetry from multispectral satellite imagery (Fig1) applies the principle that light penetration of the water column at different wavelengths is a function of the properties of sea-water. The objective of this project was to explore whether a multi-resolution bathymetric survey methodology using multispectral/hyperspectral satellite and aerial imagery (captured by drones and light aircraft) could be of comparable accuracy with traditional bathymetric survey methods.

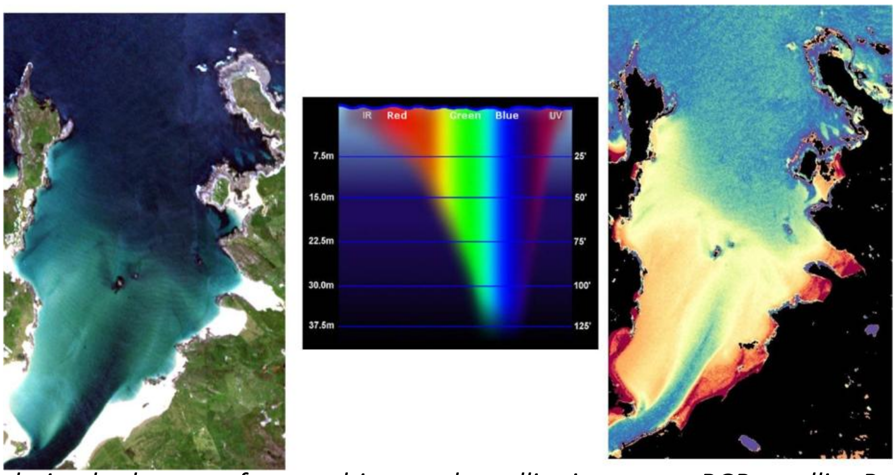



*Figure 1: Calculating bathymetry from multispectral satellite imagery – RGB satellite RapidEye image (provided under ESA licence) records information in multiple discrete 'bands'. This information can be used to calculate water depth.*

This project extended a two year SFI Industry fellowship which enabled the NCG and the GSI to collaborate on the issue. Imagery provided by the European Space Agency (ESA) was available under license from the previous study and this enabled more tests than utilising free imagery alone. Additionally, Sentinel 2a, a ESA satellite had recently become operational and would be the mainstay of future satellite derived bathymetry campaigns. It was important to incorporate this dataset when developing the methodology. Table 1 lists the results of an assessment of the imagery available for the project (excluding S2a). A decision was made to limit the spatial resolution to a maximum of 30m, ensure each image type included must have a blue band (maximum penetration of water) and finally it should coincide closely with dates of INFOMAR surveys for robust validation (not possible for the recently launched S2a).

Table 1: Suitability of satellite platforms for deriving bathymetry.

| Source | Resolution | Earliest Date | Blue band | Other Issues |
|---|---|---|---|---|
| LANDSAT 5 | 30m | 1986 | Yes | N/A |
| LANDSAT 7 | 30m | 2001 | Yes | Corrupted post 2003 |
| LANDSAT 8 | 30m | 2012 | Yes | N/A |
| OrbView 3 | 4m | 2003 | Yes | Limited imagery |
| Proba 1 | 17m | 2003 | Yes | Limited imagery |
| FORMOSAT 2 | 8m | 2004 | Yes | ISPRS Competition |
| IKONOS | 3.3m | 1999 | Yes | Discontinued by ESA |
| SPOT V | 10m | 2004 | No | N/A |
| RapidEye | 5m | 2009 | Yes | N/A |

Incorporating different platforms was essential to explore a multiresolution approach, changing the spatial resolution (pixel size), spectral resolution (number of bands and portion of spectrum covered), temporal resolution (frequency of update, seasonal variations) and radiometric resolution (bit depth) and posed the following key research questions:

## 1.1 <u>How does the spatial resolution of imagery affect spatial accuracy?</u>

The initial SFI funded study had demonstrated that the spatial resolution of the imagery significantly influenced the accuracy of the resulting bathymetric surface model. This could be varied by alternating the sensor type/range to target, using satellites, light aircraft and low flying drones (Fig 2).

*Figure 2: The multiresolution approach to deriving bathymetry (a) imagery from satellite incorporates high quality sensors and regular image updates but result in a large measurement range (b) light aircraft reduce range to target and increase resolution but are not quick to mobilise (c) drones operate on-demand at low altitude, providing high resolution images but limited by regulations and payload.*

We initially assessed the spatial accuracy of imagery from multiple separate satellites in the bathymetry calculation as illustrated in Table 2 for a range of depths. Validation was performed using INFOMAR survey data. A clear trend in the data was that the higher the spatial resolution of the data, the noisier the data, as illustrated in Fig 3b/d when compared with the 30m pixel of Landsat8 in Fig3c.

*Table 2: Spatial accuracy for the satellite bathymetry tests in Tralee bay for Sentinel 2a (10m multispectral pixel size), Landsat 8 (30m multispectral) and Pleiades (2m multispectral) satellite for a range of depths. Performance degrades at depth in turbid areas - $R^2$ for blue/green band ratio.*

| | **Full Range** | **0 to 2m** | **2 to 4m** | **4 to 6m** | **6 to 8m** | **0 to-3m** | **3 to 6m** | **6 to 9m** | **0 to 5m** | **5 to 10m** |
|---|---|---|---|---|---|---|---|---|---|---|
| **S2a** | 0.3834 | 0.0169 | 0.0000 | 0.0952 | 0.0551 | 0.0070 | 0.1603 | 0.0835 | 0.0432 | 0.2205 |
| Landsat 8 | 0.872153 | 0.153978 | 0.547615 | 0.631368 | 0.104876 | 0.519944 | 0.77285 | 0.044695 | 0.79607 | 0.371812 |
| **Pleiades** | 0.2956 | 0.0393 | 0.0277 | 0.0421 | 0.0019 | 0.1319 | 0.0475 | 0.0026 | 0.1663 | 0.0427 |

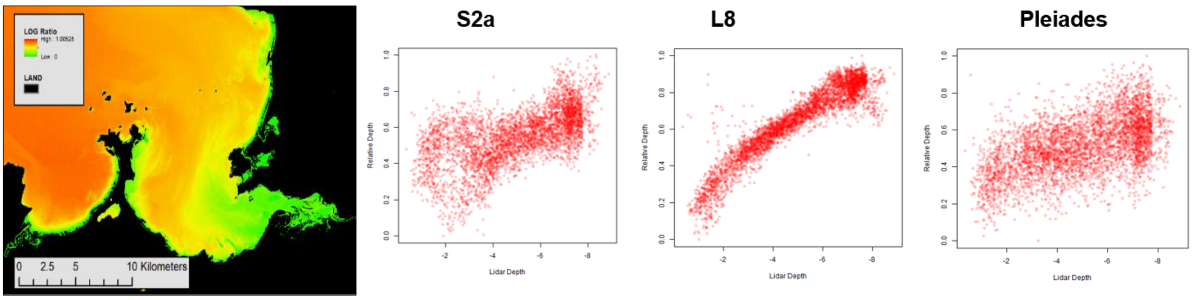
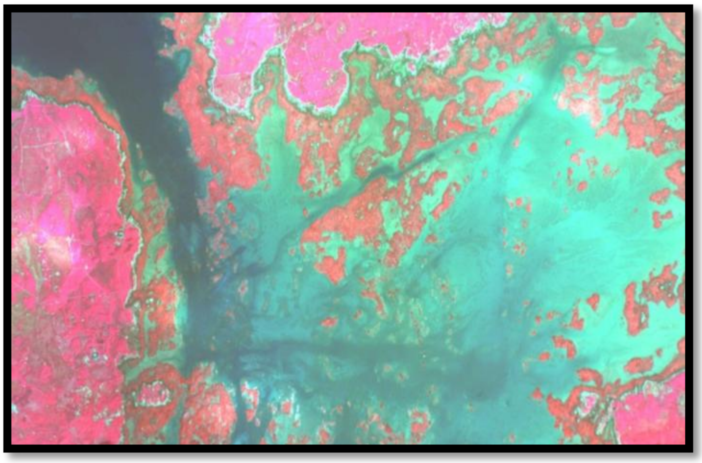



*Figure 3: Performance in Tralee bay (a) bathymetric map created for Tralee bay utilising satellite imagery (b) – (d) scatter plots of calculated v INFOMAR measured depths for the bay. High spatial resolution increases noise in the image, the 30m Landsat 8 image providing the least noisy estimate of depth. Note: different image capture dates for the satellite images inevitably result in different environmental and water conditions.*

This study was the first to explore very high resolution imagery for calculation of bathymetry. Including drones and light aircraft enabled image capture at very high resolution. Traditional terrestrial photogrammetric image matching techniques would be problematic due to a lack of matching points in overlapping imagery captured over water but their performance was better than expected (orthomosaic displayed in Fig 4a). This project also explored an optical approach similar to that applied to the satellite imagery, using the different band types to calculate depth (Fig 4b). The use of imagery recorded from drones and aircraft captured close to the target has the potential to eliminate atmospheric interference. However complications arise when identifying the exact location of an image over water. Estimates can be generated by using the airplane's on-board GPS system, however, additional instruments are needed to account for changes in the airplane's pitch/roll/yaw.



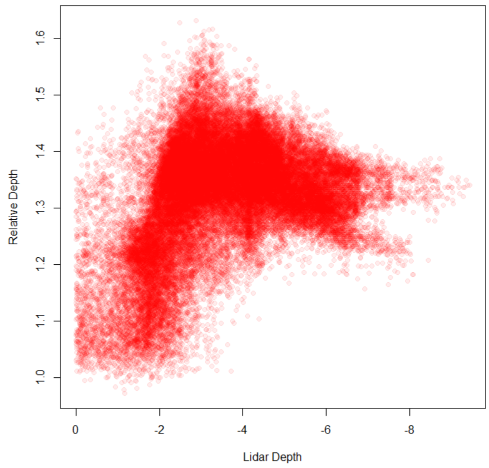



*Figure 4: Low altitude multispectral imagery (a) image stitching is possible in optically clear waters <10m depth, as matching points are visible in overlapping imagery although refraction is an issue at each image capture location (b) plot of airborne derived bathymetry through optical methods and INFOMAR data displays expected gradient/plateau at extinction depth, but the high resolution imagery has resulted in significant noise, hence the high variance.*

**<u>Key Spatial Resolution Findings</u>**

- **Environmental conditions (turbidity, waves) should be minimised for high resolution imagery.**
- **Accurate image registration is essential for aerial datasets and is critically dependant on the absolute accuracy of position and orientation measured by the navigation sensors.**
- **Traditional photogrammetric techniques are possible for low-level imagery in clear waters.**
- **Optical methods are prone to errors/noise due to the very high image resolution.**
- **Spectral data would be required to improve performance.**

## 1.2 What spectral resolution is essential for the bathymetric calculations?

Different wavelengths of light penetrate water to different depths and this is the fundamental enabling principle of bathymetric calculation through spectral measurement. Error sources that influence this calculation include the contribution of sun-glint from the sea surface and wave motion. This project explored different sun-glint removal algorithms using the NIR band. The originator of a seminal method was consulted in the project through provision of on-site training for NUIM and GSI personnel by ACRI/ARGANS exploring analytical, empirical and physics-based bathymetry methods. Sentinel 2a is a new ESA dataset and the tests we performed using this sensor in Mulroy bay (Figure 5) represent one of the very first tests of this satellite for bathymetric mapping.

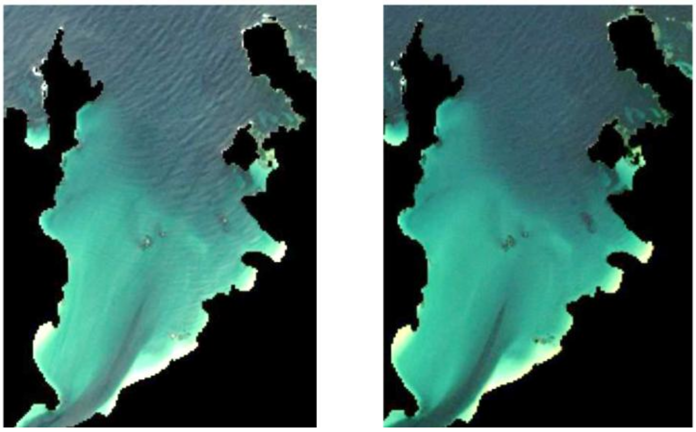


*Figure 5: Water should absorb any NIR energy before it returns from the sea-floor, so any NIR energy measured is assumed as coming from sun-glint and can be used to remove this contribution from other bands (a) a Sentinel 2a image of Mulroy bay before correction – wave motion (which generally reflects back toward the sensor) is visible (b) after correction sunglint has been successfully removed.*

Similar to the high resolution satellite imagery and multispectral imagery, some of the RGB imagery captured at low level is of very high quality and ideal for calculating bathymetry (Fig 6a), in others each wave is visible, resulting in high noise from sunglint (Fig6b). Imagery captured by a drone displayed other problems, partially due to the overlap between the spectral bands on the RGB camera which was not a dedicated multispectral sensor like that in the aerial sensor pod (which had no blue band). Additionally, flying under cloud enables image capture in cloudy conditions, unlike optical satellites, but results in spectral changes due to cloud shadow (Fig 6c). The sunglint removal methodology developed for the drone surveys was not possible for the noisy images due to the lack of an NIR band on the sensor (a Nikon RGB). This study can recommend that further tests with drones will require a multispectral camera capable of recording in both the NIR and blue portions of the spectrum, such as the "MicaSense RedEdge" camera for a follow-on study (NCG, GSI and NUIG).

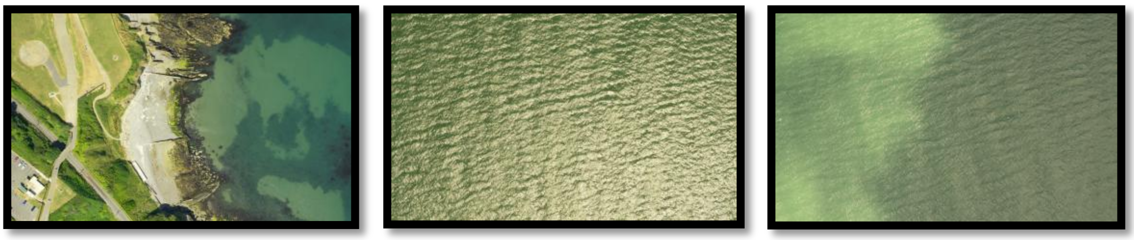


*Figure 6: Low altitude RGB imagery (a) areas in-shore are ideal for bathymetry calculation but no validation data is available in shallow regions (b) further out from the coast sunglint is an issue and a camera with a NIR band is essential for removing this error (c) flying under clouds is a strength of the low-altitude approach but cloud shadows cannot be removed using standard ratios which are common in terrestrial remote sensing for correcting illumination effects.*

Other variations in the environment affecting the imagery were assessed. Correction of atmospheric errors are a non-trivial issue, as the existence of land/sea pixels (particularly for the land/sea interface) preclude the application of traditional algorithms and four separate approaches were explored – dark object subtraction (Fig 7), log residuals, cloud shadow subtraction and 6s. A literature review identified cloud subtraction as optimal for water areas, however issues with large negative reflectance values were identified and this method was not adopted. A dataset was developed for each satellite type in Tralee bay with combinations of correction algorithms, sunglint and filters applied for assessment. This was assessed for spatial accuracy and is also the foundation for a collaboration paper looking at optimising satellite derived bathymetry accuracy using spatial prediction algorithms between NCG, GSI and a UK university.

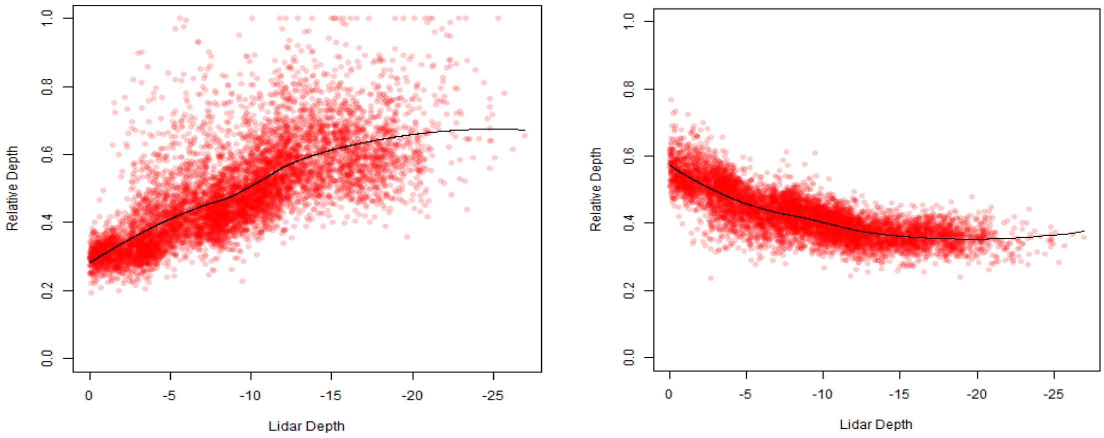



*Figure 7: Atmospheric correction of multispectral imagery (a) Top of Atmosphere Radiance (b) corrected for atmospheric effects to At Surface Reflectance inverts gradient of bathymetry calculation and reduces noise.*

**<u>Key Spectral Resolution Findings</u>**

- **Removing sunglint from low-altitude imagery requires images with a NIR band.**
- **Images can be combined from different sensors but pixel registration must be accurate.**
- **Physics based models such as 'Bomber' should be explored for suitability in Ireland.**
- **Atmospheric correction increases accuracy of bathymetry calculation. Dark Object Subtraction is sufficient although Cloud Correction approach shows potential for water.**
- **Standard drone cameras do not have discrete R, G, B bands and band overlap causes errors.**

### 1.3 Can temporal variations in the imagery be minimised?

Many influences on the imagery are temporal in nature – i.e. the time and date of year can contribute significantly to a reduction in the bathymetric accuracy. For example, times of significant rainfall will lead to increased river run-off in the coastal zone and increased turbidity in the water and this should potentially be incorporated in preliminary analysis using other GIS datasets. Blue light is more susceptible to scattering in turbid waters, and to quantify and remove this, normalized difference turbidity indices were calculated to preclude imagery from being included in the calculation if above a certain threshold. Additionally, these NDTI measurements (Fig 8) will be explored as additional predictor variables in spatial regression modelling for improving spatial accuracy in the collaboration paper.

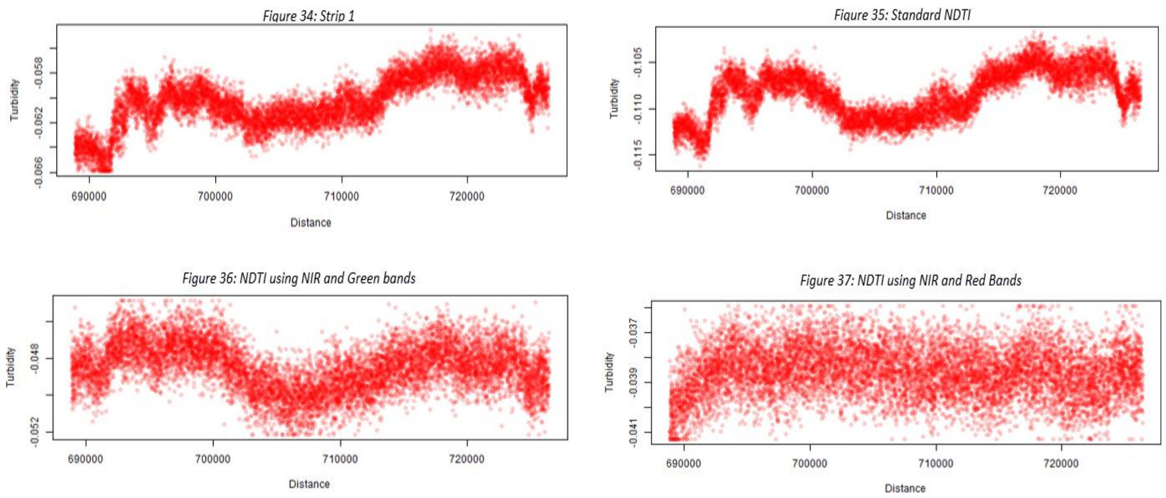



*Figure 8: Sampling turbidity throughout the test sites – high turbidity is present at river mouths, and certain locations near shore. Calculating turbidity indices can help to exclude imagery that will be problematic for bathymetric mapping and also act as additional predictor variables.*

The GSI short-call also enabled a collaboration between the NCG with the aerial sensor pod and DCU with a marine turbidity sensor. NCG operated their thermal camera during the Dublin bay survey and in return DCU provided in-situ turbidity data for the bathymetry study. These surveys were designed to coincide with a satellite overpass at Dublin bay. Data sharing enabled both groups to apply new parameters previously unavailable to them in their research.

**Key Temporal Resolution Findings**

- **Turbidity indices should be calculated to eliminate problem data.**
- **Turbidity indices provide additional predictor variables for spatial regression models.**
- **Rainfall models should be checked to correlate turbidity with river run-off in coastal bays.**
- **No significant seasonal vegetation influence spotted in test cases.**

# 2. Implementation

**2.1 Adjustments:**

The funding for the RA post was diverted into three additional tasks, greatly enhancing the project. This was an excellent opportunity, has provided additional outputs and has enabled us to identify priority areas for further research, such as physics based models and establish a collaboration between the UK training company, NUIM and the GSI. The project schedule was extended to encompass new activities:

- **Work Placement:** The timeline was extended to allow hire of a work placement. The work placement was an excellent substitute and this began in May and ended in July. The student contributed significantly and this short-call resulted in a subsequent offer of employment at NUIM.

- **Light aircraft:** Aircraft hire to include the recently developed NCG aerial sensor pod into the work-plan allowed us to include Dublin bay in the tests, as the majority of this bay was unsuitable for UAVs, being in the approaches to Dublin Airport and in the vicinity of a bird sanctuary. The light aircraft was able to hold position and coordinate with Dublin Airport control tower.

- **Training Workshop:** A training workshop was organised for NCG and GSI personnel at Maynooth University and attended by personnel from ACRI a French bathymetry firm and ARGANS, a UK bathymetry firm and a subsidiary of the ACRI group. This workshop demonstrated numerous sun-glint, atmospheric correction methodologies, masks to eliminate land and cloud in images and also highlighted the potential for a physics-based approach using the “bomber” model which has never been attempted in Irish waters. This workshop also lead to a collaboration on a presentation at the ESA Calibration Conference and work is underway on a new paper and future project application.

- **DCU Collaboration:** The extension also enabled the collaboration with the team in DCU who had the capability to measure turbidity directly with marine sensors. Dublin bay was a multi-group collaboration, with NUIM personnel involved in sensor design and calibration, a private company involved through hire of the aircraft, a NASA satellite overpass requested for that date and time and an ESA satellite orbit also expected.

**2.2 Data issues:**

Satellite remote sensing provides the best potential for regular, rapid mapping of bathymetry in coastal waters, however weather and cloud cover are particularly problematic in Ireland.

- **Environmental:** The Dublin bay collaboration coincided with a cloud cover, despite rescheduling multiple times over a number of weeks while monitoring the weather. This resulted in no multispectral satellite imagery for the Dublin bay survey which would have provided three simultaneously captured datasets for comparison. Satellite imagery from a later date was not suitable due to tide and current turbidity changes.

- **Hyperion:** EO-1 went into spacecraft safe hold on March 23, 2016 due to a GPS failure on board the satellite. Although EO-1 resumed normal operations on April 17, 2016 and the imagery was re-ordered – the satellite hyperspectral imagery requested for the test sites was never acquired.

- **Turbidity sensor:** In-situ turbidity measurements were collected in Dublin Bay with sensors towed behind a boat along varying transects of the bay covering 86 km obtaining data at 0.5m, 2m and 4m During the aerial survey of Dublin bay an offset in the calibration of the turbidity sensors from the manufacturer meant the data acquired through the DCU collaboration was unusable.

## 3. Outputs (please use bullet points)

The following outputs were specified in the project proposal and delivered:

- **D.1** - An exploration of the state of the art in multispectral/hyperspectral image processing for optical bathymetric surveying was completed and this forms the literature review for two NCG/GSI collaboration papers.
- **D.2a, D.2b** - Digital bathymetric maps of target locations in the selected priority bays have been created using Landsat 8 (30m res), Sentinel2a (10m), RapidEye (5m ) and Pleiades (2m) imagery and assessed for their spatial accuracy.
- **D.3a, D.3b** – Low altitude multispectral, thermal and hyperspectral Imagery was captured. Thermal data was provided to the DCU in the collaboration enabled by the extension to perform additional analysis.
- **D.3c, 3d** – Surface models, accuracy assessments and issues related to deriving bathymetric maps and orthomosaics from low-altitude surveys were created for transects in the target areas.
- **D.4a, D.4b** - Knowledge transfer was performed through dedicated training events focussed at building capacity in the Maynooth Research team with ACRI/Argans. Drone training was provided to NCG personnel.
- **D.5** - A report detailing the bathymetric survey findings was prepared.
- **D.6** - The research findings are being disseminated in conferences (x2), trade journals (x1) and peer-reviewed journals (1 under review, 1 in prep).

The following additional outputs arose from the study:

- **Turbidity**: Turbidity indices calculated for study of temporal resolution will be used as a predictor variable for spatial regression algorithm testing in a follow on study.
- **Platform independent:** The black-box ENVI algorithm was analysed and replicated using R code – this has provided the capability to make the methodology platform independent.
- **R Training:** In-house image processing training in R was provided to the team by the student during work placement.

## Impact/value of the project:

- **Knowledge**: The research performed during this project contributed new knowledge to the field of optical bathymetric surveying encompassing bathymetric calculation/image processing/drone operations.
- **Platforms**: The suitability of low altitude surveys for bathymetric surveying was demonstrated.
- **Methodology**: The development of a new methodology for bathymetric mapping provided a practical demonstration of the value of this project – including atmospheric correction, sun glint removal and highlighting potential of physics based models.
- **Added value from data**: Spectral, thermal and turbidity measurements captured during aerial transects in Dublin bay has added value for follow on studies.
- **Capacity Building**: The training and experience in aerial surveys, image processing and drone operations has enabled capacity building at the NCG
- **Strengthen NCG**: National and international links formed throughout the project benefit the NCG.
- **Future funding potential**: The team at Maynooth/GSI are now in a better position to apply for future funding calls in this field. The shortcall has supported a collaboration between NCG, GSI and two UK academics for a GSI Postdoctoral application.
- **Ireland and ESA**: The potential of Irish EO capability has been demonstrated.

- **Irish Universities and GSI**: The outputs advertise the work being carried out at universities in Ireland and acknowledge the support provided by the GSI.
- **Policy and governance**: The potential of satellite bathymetry has been demonstrated, providing timely and affordable near-shore depth information for coastal management applications.
- **Multidisciplinary**: Other disciplines such as coastal environmental monitoring benefit from studies such as these as they increase local knowledge by obtaining results from the specific study areas. This shortcall has supported submission of a GSI Griffith fellowship application lead by NUIG which will benefit from this study of application of drones in coastal waters for bathymetric mapping. It has demonstrated potential for sensor pods and low-altitude drones supporting a NCG collaboration with DCU for the SFI Investigators Call.
- **Employment prospects**: This project resulted in full-time employment for the student work placement.

**Appendix 1 – Publications & Presentations:**

## Presentations

Cahalane, C., Monteys, X., Magee, A., Lewis, P. and McCarthy, T (2016) Developing a rapid, low-cost bathymetric survey methodology using multi-resolution imagery. *INFOMAR Annual Seminar*, Galway, Ireland, 19$^{th}$ October 2016.

Romain, S., Martin-Lauzer F.R., Taji, M.A., Cahalane, C. (2016) Sentinel-2A/MSI L1C products' quality for coastal mapping applications and recommendations on choice of verification sites. 1$^{st}$ *Sentinel 2 Validation Team, European Space Agency Symposium, Rome, Italy*, 28$^{th}$ – 29$^{th}$ November 2016.

## Posters

Cahalane, C., Monteys, X., Magee, A., Lewis, P. and McCarthy, T (2016) Satellite Derived Bathymetry. *10th Irish Earth Observation Symposium*, Cork, Ireland, 27$^{th}$ October 2016.

Cahalane, C., Monteys, X., Magee, A., Lewis, P. and McCarthy, T (2016) Satellite Derived Bathymetry. *Atlantic Ireland*, Dublin, Ireland, 1$^{st}$ November 2016.

## Article

Cahalane, C., Monteys, X. and Hanafin, J. (2017). Improving satellite derived bathymetry *Hydro International*, in press.

## Papers

Cahalane, C., Walsh, D., Magee, A., Mannion, S., Lewis, P. and McCarthy, T. (2017). Image Fusion and Sensor Pods : Multi-resolution Surveys from a Light Aircraft. *Journal of Imaging*, **under review.**

Cahalane, C., Harris, P., Magee, A., Monteys, X., Hanafin, J. and McCarthy, T. (2017). Improving the accuracy of satellite-derived bathymetric mapping through application of spatial prediction models, **In preparation.**