Institution: University of Sheffield		
Unit of Assessment: B-10 Mathematical Sciences		
Title of case study: Weighing the world's forests from space: the BIOMASS mission		
Period when the underpinning research was undertaken: 2000–2020		
Details of staff conducting the underpinning research from the submitting unit:		
Name(s):	**Role(s) (e.g. job title):**	**Period(s) employed by submitting HEI:**
Shaun Quegan	Professor	1986–2020
Period when the claimed impact occurred: August 2013–2020		
Is this case study continued from a case study submitted in 2014? N		

1. Summary of the impact (indicative maximum 100 words)

Quantifying the amount of living vegetation and carbon stocks (biomass) in the world's forests is vital in international legislation aimed at mitigating and adapting to climate change. Our research has solved critical operational scientific problems in constructing a novel radar satellite to measure Earth's biomass. As a result, the European Space Agency has procured, from Airbus Defence and Space UK, an advanced satellite to deliver the BIOMASS mission, at a cost of €229m (£192m), with associated job and skills creation. In recognition of his scientific contributions and leadership of BIOMASS, NERC awarded Professor Quegan its 2018 Economic Impact Award.

2. Underpinning research (indicative maximum 500 words)

Forest biomass is the mass of living forest vegetation, with loss of biomass by deforestation second only to fossil fuels as a greenhouse gas source. Conversely, uptake of carbon dioxide by growing forests slows global warming and is a sustainable resource for energy and materials, as well as being essential for biodiversity. Biomass is the only internationally recognised carbon sink for offsetting greenhouse gas emissions, thus is core to policies and actions aimed at climate change mitigation.

However, determining biomass at global scale presents many scientific and technical challenges. Since 2009 Quegan, one of the lead proposers of the mission, has led an international research team developing the capability to measure biomass from space, leading to the European Space Agency's (ESA) BIOMASS project, the first spaceborne mission to use a P-band (70 cm wavelength, 435 MHz) radar with high sensitivity to biomass **[R1]**, a crucial innovation in the field. This mission uses highly innovative technology and will radically improve understanding of the worldwide distribution and dynamics of forest carbon stocks, particularly in the tropics, generating knowledge to underpin global strategies on climate change.

A key to this achievement was research showing that the ionosphere could be prevented from corrupting the biomass estimates:

a) Ionospheric Scintillation. As identified in the project proposal, scintillation (random phase changes) can defocus the radar signal and potentially destroy all features in radar images **[R2, R3]**.

- Quegan and collaborators **[R2]** showed the impact of scintillation on biomass estimation would be negligible if a dawn-dusk orbit was used.
- Scintillation effects are unavoidable at high latitudes and cause severe information disruption. University of Sheffield research contributed to correction methods for this **[R3]**, enabling measurements to be extended to polar regions.

b) Ionospheric Faraday rotation. This scrambles the polarisation measurements needed to estimate biomass. Sheffield research **[R4]** optimised the measurement and correction of Faraday rotation so that it could be reduced to negligible levels. This was a core advance.

Together, **[R2]** and **[R4]** showed that ionospheric effects can be reduced sufficiently to allow unhindered biomass estimation. This was crucial in ESA's selection of the mission. **[R3]** went further by developing scintillation correction, allowing high-latitude ice sheet measurements as a secondary mission objective.

Further scientific challenges overcome include:

- Sheffield research solved the long-standing problem of quantifying how instrument errors (polarisation impurity, phase and amplitude imbalances between radar channels, system noise) translate into biomass errors **[R5]**. This unexpectedly revealed that channel imbalance is crucial, and that the phases of the (complex) system errors have major effects, and allowed ESA to specify the instrument tolerances for Airbus to construct the instrument. Related analysis quantified the bias in estimates of Faraday rotation caused by system errors (relevant to measuring ionospheric Total Electron Content).
- Developing methods to measure in-orbit system errors using a transponder **[R6]** or natural distributed scatterers, such as forests, allowing the instrument to be calibrated in orbit, which is crucial to making accurate estimates of biomass.
- This research on instrument calibration **[R6]** and ionospheric correction **[R3]** produced methods, now embodied in the BIOMASS ground processor, needed to deliver the required signal fidelity for biomass and ice applications.

In summary, Professor Quegan's leadership of the team providing the concept and scientific and technical innovation behind ESA's BIOMASS mission, together with his provision of key scientific advances, have been fundamental in selection of the mission **[R1]**.

3. References to the research (indicative maximum of six references)

R1. Quegan, S., Le Toan T., Chave, J., Dall, J., Perrera, A. Papathanassiou, K., Rocca, F., Saatchi, S., Scipal, K., Shugart, H., Ulander, L. and Williams, M. (2012). *Report for Mission Selection: Biomass*. ESA SP 1324/1 (3 vol. series), European Space Agency, Noordwijk, the Netherlands. https://www.esa.int/About_Us/ESA_Publications/ESA_SP-1324_i_Reports_for_mission_selection_i (40 citations)

R2. Rogers, N. C., Quegan, S., Jun Su Kim, & Papathanassiou, K. P. (2013). Impacts of Ionospheric Scintillation on the BIOMASS P-Band Satellite SAR. *IEEE Transactions on Geoscience and Remote Sensing, 52*(3), 1856–1868. https://doi.org/10.1109/tgrs.2013.2255880 (44 citations)

R3. Jun Su Kim, Papathanassiou, K. P., Scheiber, R., & Quegan, S. (2015). Correcting Distortion of Polarimetric SAR Data Induced by Ionospheric Scintillation. *IEEE*

Transactions on Geoscience and Remote Sensing, 53(12), 6319–6335. https://doi.org/10.1109/tgrs.2015.2431856 (35 citations)

R4. Rogers, N. C., & Quegan, S. (2014). The Accuracy of Faraday Rotation Estimation in Satellite Synthetic Aperture Radar Images. *IEEE Transactions on Geoscience and Remote Sensing, 52*(8), 4799–4807. https://doi.org/10.1109/tgrs.2013.2284635 (25 citations)

R5. Quegan, S. & Lomas, M. R. (2015). The Interaction Between Faraday Rotation and System Effects in Synthetic Aperture Radar Measurements of Backscatter and Biomass. *IEEE Transactions on Geoscience and Remote Sensing, 53*(8), 4299–4312. https://doi.org/10.1109/tgrs.2015.2395138 (13 citations)

R6. Chen, J., Quegan, S. & Yin, X.J. (2011). Calibration of spaceborne linearly polarized low frequency SAR using polarimetric selective radar calibrators. *Progress in Electromagnetic Research*, *114*, 89-111. https://doi.org/10.2528/pier11011809 (29 citations)

4. Details of the impact (indicative maximum 750 words)

In April 2016 Airbus Defence and Space (UK) signed a €229m (£192m) contract with ESA to build the BIOMASS satellite, harnessing innovative radar technology to measure carbon stocks and changes in forests worldwide **[S1].** The mission will use all-weather imaging from space to estimate forest biomass, measure surface topography under dense forests, map subsurface structures in arid regions (including locating paleo-aquifers in desert regions as new water sources), and contribute to observations of ice sheet dynamics.

Economic impact

The contract was underpinned by research from an international team led by Quegan, producing a compelling scientific case for BIOMASS and [Text removed for publication] **[R1, S1, S2]**. Sharing scientific and technical knowledge through publications and presentations, and working with ESA, enabled knowledge transfer to Airbus UK with their strengths in radar missions. [Text removed for publication]. BIOMASS launch is scheduled for 2023.

In recognition of this achievement, the Natural Environment Research Council (NERC) awarded Professor Quegan its 2018 three-yearly Economic Impact Award **[S4]**.

Impact on organisations

Quegan's expertise in leading highly multidisciplinary, multi-institutional teams while directing the Centre for Terrestrial Carbon Dynamics and the Carbon Cycle Theme in the UK's National Centre for Earth Observation allowed him to combine the diverse talents needed to overcome the many scientific and technical challenges of BIOMASS.

BIOMASS has led to significant organisational development in both ESA and NASA **[S5]**. NASA has two space missions dedicated to forest structure and biomass: i) the Global Environmental Dynamics Investigation lidar, deployed on the International Space Station in November 2018, and ii) NISAR (NASA-ISRO Synthetic Aperture Radar), a radar operating at 1/3 of the BIOMASS wavelength, scheduled for launch in 2022. These three highly complementary missions have led to unprecedented agreement between the ESA and NASA to develop a common Mission Algorithm and Analysis Platform (MAAP) **[S5]**.

This will host the data from all three missions, providing processing resources for users to analyse the huge data quantities and develop and validate new algorithms against reference data and information. This is a paradigm shift from moving vast amounts of data to moving only analysed results. MAAP is already functioning and contains the full set of data from earlier joint ESA/NASA airborne radar and lidar campaigns in Gabon in 2015 and 2016, together with *in situ* reference data. This illustrates this new level of inter-agency working.

Impact on BIOMASS design, specification, and satellite construction

Quegan's contributions were particularly important, [Text removed for publication] **[S2, S3, R3]**.

Quegan's research findings led ESA to select a dawn-to-dusk BIOMASS orbit. While this prevents loss of forest information, the researchers also developed methods to correct unavoidable scintillations at high latitudes **[R3].** This enables measurement of icesheet motion over polar regions as a secondary BIOMASS objective **[R1, S6].**

[Text removed for publication]. A related issue is confirming the instrument meets its specification when in orbit and calibrating it if not.

[Text removed for publication].

In addition, methods to monitor instrument performance without additional cost using the Amazon forests as a natural distributed scatterer were developed **[S8].**

5. Sources to corroborate the impact (indicative maximum of 10 references)

S1. Press release announcing Airbus construction of satellite 3 May 2016: https://www.airbus.com/newsroom/press-releases/en/2016/05/airbus-defence-and-space-signs-contract-to-build-biomass-the-european-space-agencys-forest-mission.html

S2. [Text removed for publication]**.**

S3. [Text removed for publication].

S4. 2018 NERC Economic impact award winner Prof Shaun Quegan. Webpage and application NERC - NERC 2018 Impact Awards. https://nerc.ukri.org/latest/events/impact/

S5. Albinet, C., Whitehurst, A. S., Jewell, L. A., Bugbee, K., Laur, H., Murphy, K. J., Frommknecht, B., Scipal, K., Costa, G., Jai, B., Ramachandran, R., Lavalle, M., & Duncanson, L. (2019). A Joint ESA-NASA Multi-mission Algorithm and Analysis Platform (MAAP) for Biomass, NISAR, and GEDI. *Surveys in Geophysics, 40*(4), 1017–1027. https://doi.org/10.1007/s10712-019-09541-z

S6. Quegan, S., Le Toan, T., Chave, J., Dall, J., Exbrayat, J.-F., Minh, D. H. T., Lomas, M., D'Alessandro, M. M., Paillou, P., Papathanassiou, K., Rocca, F., Saatchi, S., Scipal, K., Shugart, H., Smallman, T. L., Soja, M. J., Tebaldini, S., Ulander, L., Villard, L., & Williams, M. (2019). The European Space Agency BIOMASS mission: Measuring forest above-ground biomass from space. *Remote Sensing of Environment, 227*, 44–60. https://doi.org/10.1016/j.rse.2019.03.032

S7. *Analysis of calibration inaccuracies on Biomass estimates of Faraday rotation, backscatter and biomass* (2014) Final Report on CCN4 to ESA/ESTEC Contract No. 22849/09/NL/JA/ef.

S8.	*Biomass External Calibration Study*, Final Report (2017), ESA/ESTEC Contract No. 4000116784/15/NL/CT.