Institution: University of Surrey		
Unit of Assessment: 12 Engineering		
Title of case study: Advancing earth imagery through the management of micro-vibrations in satellites.		
Period when the underpinning research was undertaken: 2013-2019		
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:**
Professor Guglielmo Aglietti	RAEng/SSTL Research Chair in Space Engineering, and Director of Surrey Space Centre	December 2012 - present
Period when the claimed impact occurred: August 2013 – December 2020		
Is this case study continued from a case study submitted in 2014? N		

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

High-resolution imagery from Earth Observation (EO) satellites is essential for applications such as rapid disaster response, agriculture and urban planning. Micro-vibrations arising from mechanical disturbances on board spacecraft adversely affect image quality. Research from Surrey Space Centre characterising and modelling micro-vibrations and innovative active micro-vibration control techniques were applied in commercial EO satellites TripleSat/DMC3 Constellation and SSTL-S1. Further impact has been realised through the commercial application of high-resolution imagery, facilitation of international disaster responses, and informing standards for engineering practice for spacecraft development.

2. Underpinning research (indicative maximum 500 words)

The Surrey Space Centre (University of Surrey) – led by Professor Aglietti (2014-2019) - has been at the forefront of small satellite technology since its inception in 1979.

Micro-vibrations – low-level mechanical disturbances on board spacecraft - are an issue of growing importance as some modern payloads, and in particular, the new generations of optical instruments, require extreme platform stability. Micro-vibrations are generally produced by internal mechanisms on board spacecraft, including reaction wheel assemblies (RWAs), momentum wheel assemblies, cryo-coolers, and solar and antenna pointing mechanisms, with RWAs considered the most significant source. The low-level of these micro-vibrations coupled with their wide frequency range (from sub hertz to hundred hertz) makes their modelling and analysis a significant challenge. There was, therefore a need for a model which (i) gives accurate estimates covering a wide frequency range, (ii) reduces the personnel and time costs associated with conducting an extensive experimental test campaign, and (iii) reduces the computational effort without affecting the quality of the result.

Modelling micro-vibrations

Various approaches have been considered to address the issues related to micro-vibration predictions. The industry-standard approach is the Stochastic Finite Element Method (SFEM) of which the Monte Carlo Simulation (MCS) - the simplest method for treating the response variability calculation in the framework of SFEM - is the most well-known. However, it is well documented that at frequencies beyond the first few modes of a system, SFEM is unsuitable for obtaining efficient predictions for micro-vibrations.

In response, Aglietti and his team proposed merging the efficiency of the Craig-Bampton reduction technique (CB) with the simplicity and reliability of MCS to produce an overall analysis methodology to evaluate the dynamic response of large structural assemblies in the mid-frequency range, extending it to the case when multiple sources of micro-vibrations act simultaneously on the same structure. The method succeeds in producing results very similar to those from a full MCS while reducing drastically the computational effort involved. This is particularly valuable in the space industry, as different parts of the satellite usually have different levels of maturity, characterised by different levels of uncertainty in their parameters **[R1, R2].**

The resulting computational procedure was applied to the new high-resolution SSTL-300-S1 satellite (launched 2018), and the predictions compared with the experimental results retrieved during the physical micro-vibration testing of the satellite **[R1, R2, R3]**.

Measurement of disturbances induced by the reaction wheel assembly

The primary challenge in satellite micro-vibration analysis is the characterisation of the potential disturbance sources. For this, accurate measurement is essential. Current practice in the space industry is to use the outcomes from the hard-mounted RWA configuration measurements as direct inputs for micro-vibration analysis. However, Aglietti argues that this method is fundamentally flawed as it does not represent real-world operating conditions where the RWA is mounted on a flexible structure. In **[R3]**, Aglietti and his team consider a cantilever configured RWA [developed by Aglietti] and present a mathematical model to describe its dynamics. The model was implemented to predict the dynamic mass of the RWA in both static and operative conditions. The team demonstrated that predictions derived from the traditional approach ignored significant characteristics of the system response. Application of correcting factors (i.e. supporting structure dynamic masses) considerably improved the agreement between analytical estimates and test results. The inclusion of the gyroscopic effect in the RWA internal dynamics characterisation further improved predictions.

Micro-vibration control techniques

Active (as opposed to passive) control techniques are often required to mitigate sources of micro-vibrations on board spacecraft. However, reliability issues and additional electrical power use are major drawbacks of active control techniques, such as active isolation systems, limiting their usefulness.

Aglietti's team proposed an electromagnetic shunt damper (EMSD) connected to a negative-resistance circuit. The negative resistance produces an overall reduction of the circuit resistance resulting in an increase of the induced current in the closed circuit. This damper can be classified as semi-active since it does not require any control algorithm to operate and has low power requirements, simplified electronics and small device mass. The damper was shown (analytically and experimentally) to be capable of effectively isolating typical satellite micro-vibration sources **[R4, R5]**.

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

[R1] Remedia, M., **Aglietti, G.S.,** Richardson, G., and Sweeting, M. (2015). 'Integrated semi empirical methodology for microvibration prediction'. *AIAA Journal*, 53 (5), pp. 1236-1250. DOI: 10.2514/1.J053339

[R2] Remedia, M., **Aglietti, G.S**., and Richardson, G. (2015). 'A Stochastic Methodology for Predictions of the Environment Created by Multiple Microvibration Sources'. *Journal of Sound and Vibration,* 344, pp.138-157. DOI: 10.1016/j.jsv.2015.01.035

[R3] Addari, D., **Aglietti, G.S.**, and Remedia, M. (2017). 'Experimental and numerical investigation of coupled microvibration dynamics for satellite reaction wheels'. *Journal of Sound and Vibration*, 386. pp. 225-241. DOI: 10.1016/j.jsv.2016.10.003

[R4] Richardson, G., Smet, G., **Aglietti, G.**, Seabrook, T., and Alsami, S. (2014). Managing micro-vibration on the SSTL-300 S1 a 400 kg 1 m resolution Earth imaging satellite.

Proceedings of the13th European Conference on Spacecraft Structures, Materials & Environmental Testing (SSMET), Braunschweig, Germany, April 1-4, 2014, ESA SP-727

[R5] Stabile, A., **Aglietti**, **G.S.**, Richardson, G., and Smet, G. (2017). 'Design and verification of a negative resistance electromagnetic shunt damper for spacecraft micro-vibration' *Journal of Sound and Vibration*, 386 pp 38-49. DOI: 10.1016/j.jsv.2016.09.024

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

Aglietti's research on satellite micro-vibrations **[R1-R5]** has directly impacted the ability of Surrey Satellite Technology Ltd. (SSTL) to produce satellites that achieve the platform stability required for high-resolution imagery (<1m). Data and high-resolution images from these satellites offer significant benefits to both distributors and end-users.

Adoption of technology in commercial satellites and setting the industry standard
The TripleSat/DMC3 (launched in 2015) is a Disaster Monitoring Constellation (DMC) made up of three SSTL-300S1 satellites. As a direct result of Aglietti's micro-vibration research **[R1-R5]**, SSTL were able to mitigate micro-vibrations in the TripleSat/DMC3 satellites by redesigning the RWA isolation system located at the base of the SSTL-300S1 platform, which had been the dominant source of micro-vibration **[S1]**. This mitigation resulted in significant improvements in platform stability. The Chief Technology Officer (CTO) of SSTL stated, "*Professor Aglietti's research work <…> directly contributed to SSTL development strategy for higher resolution imagery and more cost effective EO [Earth Observation] spacecraft and future missions*." **[S2]**

TripleSat/DMC3 is owned by SSTL and managed under licence on behalf of Twenty First Century Aerospace Technology (21AT). 21AT paid SSTL £110M for their services, leasing 100% of the image capacity of the three satellites for the first 7 years **[S3]**.

In 2018, SSTL launched another EO satellite (SSTL-S1) utilising the same SSTL-300 platform technology as TripleSat/DMC3. The high-resolution imagery data from this satellite is leased to 21AT and Airbus for a contract value of £25M **[S4]**. SSTL continue to apply the outcomes of Aglietti's research team in subsequent high-resolution EO satellites.

Aglietti's micro-vibration expertise also contributed to the ECSS-E-HB-32-26 standard, "Spacecraft mechanical loads analysis handbook" (European Cooperation for Space Standardisation), drawing on techniques detailed under a European Space Agency contract **[S5]**. This standard has been the recommended engineering practice for European developers of space systems throughout the REF period and remains the current standard today.

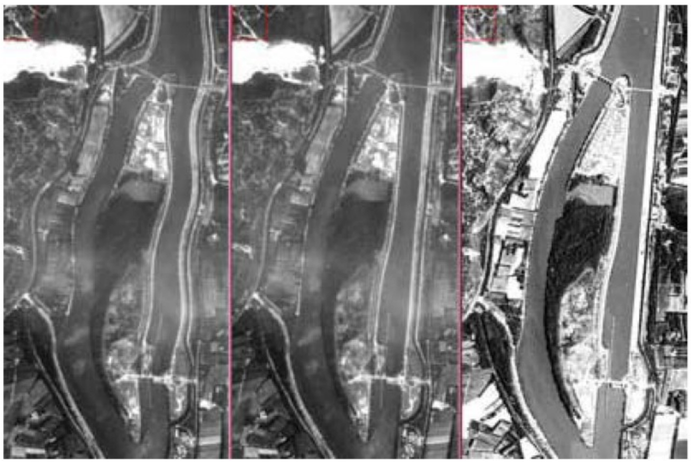
Enabling Access to High-Resolution Imagery
There is a need from multiple market sectors for high-resolution images for applications such as urban planning, crop yield calculation, pollution monitoring and biodiversity assessment **[S6]**. Indeed, sales of EO space systems by the European space manufacturing industry reached €1.9billion in 2017, representing ~21% of all European space systems manufacturing revenues [Source: Copernicus Market report, 2019].

The TripleSat/DMC3 Constellation consists of three identical ultra-high-resolution optical satellites that can survey any point of the globe on a daily basis delivering 0.8m (panchromatic) and 4m ground sampling distance (GSD) multispectral high-resolution imagery with a 23.4K swath. The high-resolution imagery from TripleSat/DMC3 Constellation data is being distributed by organisations including Satellite Imaging Corporation (SIC) **[S7]** and Earth-i **[S8]**. On 10 April 2018, Airbus entered into an agreement with satellite operator 21AT to distribute the images acquired by their TripleSat constellation.

Earth-i is a Geo-Spatial Information provider. Earth-i partnered with suppliers SSTL and 21AT to provide EO data and services from the TripleSat/DMC3 constellation to business, government, traders, investors, and NGOs since its launch as a start-up in 2015. In 2019/20, Earth-i employed a staff of 31 with a turnover of £1.9M (Companies House) and is ranked in the top ten most important and influential companies in the global space industry according to the 2018/19 Global Ranking Report **[S8]**.

Image use case example from Earth-i: Advanced Coffee Crop Optimisation for Rural Development (ACCORD)

Coffee is one of the world's premium quality crops, but farmers lack access to timely and accurate weather data to help them improve their yield and farming practices. ACCORD provides proactive, targeted crop management information to improve the livelihoods and incomes of smallholder coffee farmers in Rwanda and Kenya. The crop management advice delivered via a mobile app is derived from satellite Earth observation (including TripleSat/DMC3) and advanced micro-climate information. The information helps to make significant improvements to coffee crop quality and yield, allowing farmers to achieve higher incomes for their work and improve the quality of life for their families **[S9]**.



Figures 1. Left and centre images illustrate the effect of different levels of micro-vibrations; on the right is a micro-vibration free image. Source: European Space Agency Handbook **[S5]**

Aiding Disaster Relief

The TripleSat/DMC3 contributes images and data to the International Charter 'Space and Major Disaster' (disastercharter.org) - a worldwide collaboration under which satellite data are made freely available for humanitarian use in the event of major international disasters. The primary users of this data under this charter are disaster relief organisations, for whom accurate and locationally precise information on the damage caused is vital for prioritised, coordinated and safe rescue and relief operations. Satellite imagery data enable large areas to be reviewed at speed and rescue activities to be accelerated.

The following are examples of how the high-resolution images from the disaster monitoring constellation TripleSat/DMC3 have been used to support disaster responses:

- Images provided to the agencies in charge of the disaster response for the Fort McMurray wildfires in Alberta, Canada (May 2016) **[S10].**
- Mapping of an earthquake and tsunami on New Zealand (Kaikoura) (November 2016). A Linked Open Data for Global Disaster (LODGD) Task Group report following the tsunami states, "*During the Kaikoura earthquake, Integrated Research on Disaster Risk (IRDR's) Disaster Loss DATA project and CODATA Task Group Linked Open Data for Global Disaster Risk Research (LODGD) worked together with Tonkin + Taylor International (T+TI) to provide TripleSat satellite images of the affected Hurunui District. Geo-spatial information was developed for the New Zealand Earthquake Commission (EQC) on the damage caused, and was made available through a web-based viewer to all government agencies, response and recovery agencies, engineers and researchers, thereby informing first response and mitigation measure*." **[S11]**

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

Adoption of technology

[S1] Evidence of micro-vibration mitigations on DCM3, (Aglietti; reference 11) https://directory.eoportal.org/web/eoportal/satellite-missions/d/dmc-3

[S2] Testimonial from CTO of SSTL, 2018. (PDF)

[S3] Launch and contract value of £110M for the DMC3/Triplesat constellation: https://www.sstl.co.uk/space-portfolio/launched-missions/2010-2019/dmc3-triplesat-constellation-launched-2015

[S4] contract value of £25M for further SSTL-S1 satellite data https://www.sstl.co.uk/media-hub/latest-news/2018/sstl-and-21at-announce-new-earth-observation-data-

[S5] ECSS-E-HB-32-26 Standard http://www.vibrationdata.com/tutorials2/ECSS-E-HB-32-26A_19February2013.pdf refers to Aglietti contributing to Sections 4.6.2, 13.4.3.3 and refers to *Methodology for analysis of structure-borne micro-vibrations - Disturbance source modeling and associated experimental techniques ", Technical Note 2, ESA Contract 4000101914/10/NL/RA, 2010*

Enabling High resolution imagery

[S6] BBC website discussing the use of the TripleSat data https://www.bbc.co.uk/news/science-environment-34255622

[S7] Satellite Imaging cooperation use of TripleSat/DMC3 imaging https://www.satimagingcorp.com/satellite-sensors/triplesat-satellite/

[S8] Earth-i use of DCM3 constellation https://earthi.space/constellations/ and 2018/19 Global Ranking https://earthi.space/news/page/17/

[S9] Earth-i Advanced Coffee Crop Optimisation for Rural Development (ACCORD) project using DCM3 imaging: UKSA UK Space Sector Catalogue (page 30) UK Space Sector Catalogue (publishing.service.gov.uk)

Aiding Disaster relief

[S10] Use of TripleSat/DMC3 data for fires in Alberta (Canada) https://earthi.space/blog/active-fires-in-canada/

[S11] Mapping following earthquake and Tsunami on New Zealand cost (Kaikoura) http://www.csdata.org/en/p/205/3/#Ch-S4