Institution: University of Bradford

Unit of Assessment: B11 Computer Science

Title: Automated Solar Activity Prediction (ASAP) system makes prediction of solar activity faster, automated and more accurate

Period when the underpinning research was undertaken: 2006 to present

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:
Prof Rami Qahwaji	Professor of Visual Computing	2002 - present
Dr Tufan Colak	PDRA	2006 - 2014
Dr Omar Ashamari	PDRA	2010 - 2016

Period when the claimed impact occurred: 1 Aug 2013 – 31 Dec 2020

Is this case study continued from a case study submitted in 2014? No

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

Significant solar storms can damage satellites, radio communications, and power grids. Predicting them has been a challenging problem for experts. We developed one of the world's first automated real-time systems for the 24/7 monitoring and prediction of extreme solar flares by processing the latest satellite images. ASAP (Automated Solar Activity Prediction) is publicly available at http://spaceweather.inf.brad.ac.uk/. ASAP is working with NASA's Solar Dynamics Observatory satellite, integrated into NASA's online space weather portal, used as a decision-making tool for NASA's robotic missions and to manage radiation effects on NASA's Chandra x-ray observatory orbit, and is widely acknowledged as an international benchmark.

2. Underpinning research (indicative maximum 500 words)

Solar flares and Coronal Mass Ejections (CMEs) are solar eruptions that emit vast quantities of radiation and charged particles into space. These events can damage the Earth's communication and power infrastructure, resulting in power outages and reduced system functionality. Predicting these events to ensure systems and infrastructure are robust has long been a challenging problem for experts.

We tackled this problem from an imaging/AI perspective. Between 2005 and 2010, our approach focused on extracting relevant solar features from multi-wavelength satellite images before feeding them to AI systems trained on years of data, to generate automated solar flare predictions [1,2,3]. ASAP was created by integrating the solar imaging module and the solar AI module. ASAP was integrated with NASA's Community Coordinated Modelling Center (CCMC) and became operational in 2010. ASAP was updated in 2011 to support the newly launched Solar Dynamics Observatory (SDO) satellite and again in 2016 to improve its prediction accuracy and overall performance. It is still operational 24/7, providing automated web-compliant real-time predictions.

ASAP was also integrated with ESA's Space Weather European Network (SWENET), between 2011 and 2013. SWENET is no longer operational, but to improve launch safety, ESA funded two ASAP updates in 2013 and 2015 to integrate it with the University of Malaga's (Spain) Solar Energetic Particles (SEPs) prediction system, automating SEPs prediction for different forecast windows [4].

Developing the Imaging Module

We developed novel imaging techniques for the automatic pre-processing, detection and feature extraction of solar features (e.g. active regions, sunspots, filaments) captured by the Michelson Doppler Imager (MDI) instrument on-board NASA's Solar and Heliospheric Observatory (SOHO) satellite. In 2008, we introduced the first automated and real-time system to classify sunspots based on the McIntosh classification system [3], which became the cornerstone for ASAP [2]. Before that, the classification of sunspots was a manual time-consuming process that was carried out by experts.

Developing the AI Module

The AI module extracts knowledge from various solar catalogues/images and represents this knowledge in computerised learning rules. ASAP's predictions are generated by comparing the feature patterns detected by the imaging module with the knowledge extracted by the AI module. We started by developing new data mining technology to investigate the correlation between solar events and solar features. This technology [1,3,5] was used to extract knowledge from the following catalogues: SMART Magnetic Features Catalogue produced by Trinity College Dublin, National Geophysical Data Centre (NGDC) Solar Flares Catalogue, NGDC filament catalogue, SOHO/LASCO CME catalogue, and NGDC sunspots Catalogue. We modified our machine learning technology to investigate the feasibility of CMEs prediction by associating CMEs events with flares [6] and filaments [1].

Integrating the Imaging and AI Modules to Create ASAP

The performance of the integrated system (published in 2009) was tested based on the EU COST action ES0803 space weather metrics. NASA organised two specialised workshops (USA 2009 and Japan 2018) for comparing leading global flares prediction models, which resulted in key joint publications, such as [7]. ASAP performed well in both workshops and is recognised as a major player in this global effort and an international benchmark.

This research was conducted under the supervision of Prof. Rami Qahwaji (2005 to present), with significant input from two PDRAs, Dr. Tufan Colak (2006 - 2014) and Dr Omar Ashamari (2010- 2016) alongside four research students.

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

1. Al-Omari M, Qahwaji R, Colak T and Ipson S S (2010): "Machine Learning-based Investigation of the Associations Between CMEs and Filaments" *Solar Physics*, 262 (2): 511. https://doi.org/10.1007/s11207-010-9516-5

2. Colak T and Qahwaji R (2009): "ASAP: A Hybrid Computer Platform Using Machine Learning and Solar Imaging for Automated Prediction of Significant Solar Flares" *Space Weather*, 7, S06001. https://doi.org/10.1029/2008SW000401

3. Colak T and Qahwaji R (2008): "Automated McIntosh-based classification of sunspot groups using MDI images" Solar Physics, 248 (2): 277-296. https://doi.org/10.1007/s11207-007-9094-3

4. García-Rigo A, Núñez M, Q R, Ashamari O and Jiggens O (2016): "Prediction and warning system of SEP events and solar flares for risk estimation in space launch operations" *Journal of Space Weather and Space Climate*, 6 https://doi.org/10.1051/swsc/2016021

5. Ahmed O, Qahwaji R, Colak T, Higgins P and et al P (2013): "Solar Flare Prediction Using Advanced Feature Extraction, Machine Learning, and Feature Selection" *Solar Physics*, 283 (1): 157-175. https://doi.org/10.1007/s11207-011-9896-1

6. Qahwaji R, Colak T, Al-Omari M and Ipson S (2008): "Automated prediction of CMEs using machine learning of CME–flare associations" Solar Physics 248 (2), 471-483 https://doi.org/10.1007/s11207-007-9108-1

7. Barnes G, Leka KD, Schrijver C, Colak T and Qahwaji R (2016): "A comparison of flare forecasting methods, I: Results from the “All-Clear” Workshop" *The Astrophysical Journal*, 829 (89) https://doi.org/10.3847/0004-637X/829/2/89

Grants

Qahwaji, R. Image Processing and Machine Learning Techniques for Short-Term Prediction of Solar Activity (GR/T17588/01). EPSRC. 2005 – 2008. GBP124,887.

Qahwaji, R. Image Processing, Machine Learning and Geometric Modelling for the 3D Representation of Solar Features (EP/F022948/1). EPSRC. 2008 – 2011. GBP293,394.

Qahwaji, R. Solar Events Prediction system For Space Launch Risk Estimation (with Technical University of Catalonia and the University of Malaga). European Space Agency. 2013 – 2014. EUR100,000.

Qahwaji, R. First European Comprehensive SOLar Irradiance Data exploitation (Grant ID 313188). European Commission FP7. 2012 - 2015. EUR1,994,373.60. EU contribution to University of Bradford: EUR247,082.

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

ASAP's Impact on Major Space Agencies

For key decision-makers, the primary source of information on potential space weather threats is NASA's Community Coordinated Modelling Center (CCMC). ASAP has been integrated with CCMC since 2010, where it is currently operational 24/7 in an automated real-time manner [A-C]. ASAP, as part of CCMC, is regularly used to provide space weather analysis by NASA's robotic mission operators [A].

ASAP predictions (current and historical) are available publicly on NASA's CCMC portal to a variety of space weather agencies, industries, and users. This enables world-wide community involvement in real-time predictions, fosters community validation projects and helps researchers improve their forecasts [A]. CCMC users include power companies, satellite operators, aviation companies, insurance companies, and meteorological institutes. ASAP is used by space weather forecasters at NASA's Goddard Space Flight Center (GSFC) Space Weather Research Centre (SWRC). ASAP is used routinely in forecast displays designed by the SWRC staff. SWRC acknowledges that ASAP "*has proved to provide additional information that allows forecasters to build a more complete picture of space weather conditions throughout the solar system*". ASAP's real-time predictions provide NASA's operators with improved predictions of future disturbances in space, which could affect robotic missions in terms of communications, planned activities and orbit. NASA has also integrated ASAP into their Space Weather Explorer (SWX) app [D], which is available for Android and iOS devices. The android app has been downloaded more than 10,000 times, according to Google Play [D]. Citizen scientists can easily access, download and make videos from CCMC models including ASAP's data in order to engage many different groups of people to improve educational experiences and expand the public understanding of space weather, for example, in 2018, a YouTube video discussing ASAP was made (in Portuguese), which has been viewed almost 50,000 times.

ASAP is currently used to inform the operation of the Chandra x-ray observatory, NASA's Flagship-class space telescope, of solar radiation that could affect Chandra's orbit. As stated by NASA's Marshall Space Flight Center [E] *"ASAP is one of several space-weather indicators used to inform Chandra operations of the recent, current, and projected radiation environment in Chandra's highly elliptical orbit. Chandra's radiation-management strategy uses these indicators combined with protective actions (stowing the CCDs in high-radiation environments) to limit further degradation of the front-illuminated devices to acceptable levels."*. An active link to ASAP's predictions is permanently displayed on Chandra's web page.

The on-board electronics of launch vehicles, satellites, and other space systems are susceptible to radiation-induced effects caused by solar storms. High energy particle radiation, caused by solar flares, is the main concern for mission launchers. ASAP was used as a pre-launch model for ESA during the SEPFlares ESA-funded project (ESA ITT Ref: AO/1-7430/13/NL/AK) [F], where it was used to automate the Solar Energetic Particles prediction model, developed by the

Universidad de Málaga (Spain). This project delivered new ESA capability to predict solar flares and SEP events and generate warning alerts on safe/unsafe conditions for launch operators.

ASAP's Prediction of Real-life Events

Significant solar flares are not very frequent, but they could have serious consequences for different industries. As an example, large flares occurred on 11 March 2015 (X2.2 flare), 6 Sep 2017 (X9.3 flare) and again on 6 Sep 2017 (X2.2. flare). According to SWPC, they disturbed radio communications causing a temporary blackout of high-frequency radio transmissions on the daylight side of Earth. Low frequency communication, used in navigation, was degraded for an hour. ASAP managed to predict these events successfully at least 6 hours before they actually occurred, as shown below.

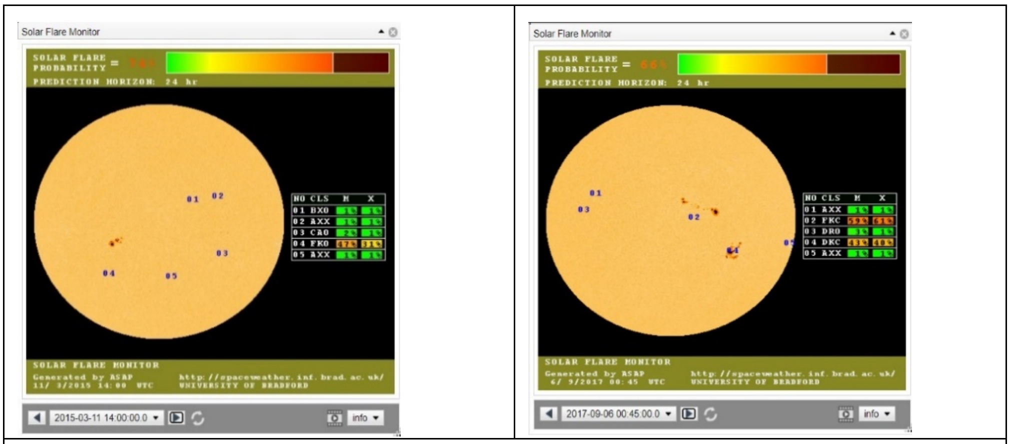

Figure 1. ASAP's predictions generated several hours before the actual X-class flares in 2015 and 2017, shown in CCMC's portal

Improving the Input to Climate Change Models

ASAP's imaging/AI technology played key role in the EU FP7 project "SOLID: First European Comprehensive SOLar Irradiance Data exploitation", enabling the release of SLID's major delivery, which is the Observational Solar spectral irradiance (SSI) composite [G]. Variations in SSI are an important driver of the temperature, chemistry and dynamics of the Earth's atmosphere and ultimately the Earth's climate. The SOLID project observational composite is used as an independent validation of the SSI dataset recommended for the next generation CMIP6 (Coupled Model Intercomparison Projects) climate model intercomparison [G].

Further Impact and Outreach

Because of the significance of ASAP's 24/7 real-time predictions, they are displayed on a number of renowned scientific websites such as: Harvard's University Replan Centre (US), Hvar Observatory (Croatia), amateur radio community pages, and citizen science websites NONBH and Deep Sky Observer. A link to ASAP's prediction is also available permanently by leaders in this field such as the Royal Observatory of Belgium Solar Influences Data analysis Center (SIDC) website. SIDC is a partner in the Solar-Terrestrial Center of Excellence (STCE). Another link is also available at NASA'S Reuven Ramaty High Energy Solar Spectroscopic Imager (RHESSI) Mission.

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

[A]. Testimonial Letter – NASA

[B]. NASA's CCMC website https://ccmc.gsfc.nasa.gov/challenges/flare.php

[C]. Corroborator: Research Astrophysicist. NASA Goddard Space Flight Center

[D] https://ccmc.gsfc.nasa.gov/SWX/swxweb.php; Android and iOS apps download sites: NASA Space Weather – Apps on Google Play

[E]. Testimonial Letter – NASA's Chandra Mission

[F]. The ESA Funded Project and model "SEPsFLAREs project" (ESA contract No. 4000109626/13/NL/AK) funded by ESA/ESTEC Space Environment (TECEES) section https://upcommons.upc.edu/bitstream/handle/2117/86097/201511_ESWW2015_Poster_A0_SEPsFLAREs_v9.pdf

[G]. The FP7 SOLID project webpage: https://projects.pmodwrc.ch/solid/index.php/main-database