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SEAHAWK: A Nanosatellite Mission for Sustained Ocean Observation

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ABSTRACT

In a recent report, the US National Academy of Science has highlighted the need for sustained, advanced ocean colour research and operations. The report shows that ocean colour satellites provide a unique vantage point for observing the changing biology of our ocean's surface. Space observations have transformed biological oceanography and are critical to advance our knowledge of how such changes affect important elemental cycles, such as the carbon and nitrogen cycles, and how the ocean's biological processes influence the climate system. Many coastal applications—such as monitoring for Harmful Algal Blooms (HABs), ecosystem-based fisheries management, and research on benthic habitats including coral reefs and coastal wetlands—require greater spatial resolution than is currently available to resolve the complex optical signals that coastal waters produce. To combat this a team of scientists and engineers in the UK and United States have come together to develop a high resolution ocean colour sensor capable of integration with a custom designed 3U nanosatellite, termed Seahawk.

The aim of this paper is to describe the technical and science objectives of the mission, as well as outlining the technical challenges and initial design of the Ocean Colour payload and the supporting spacecraft platform. Clearly this is a very ambitious mission with particular challenges not only in the development of an advanced payload of this type – capable of fitting within the constraints of a 3U CubeSat – but also in the platform in terms of power, attitude control, and data processing. The SeaHawk team expects that these demanding requirements will result in a CubeSat that challenges the very limits of what is possible on this size of spacecraft.

KEYWORDS: CubeSat, Ocean Colour Monitoring, Multispectral, SOCON, SeaHawk, HawkEye, Moore's Law, SeaWiFS

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1. INTRODUCTION AND BACKGROUND

History

Ocean colour data provides information on the presence of sediments and phytoplankton, and the type and concentration of phytoplankton in particular can be a key indicator of the environmental conditions in our oceans. As a result, the key role that ocean colour data and ocean colour monitoring can play in our understanding of the environment is becoming ever clearer to the wider scientific community and, with over 70% of the Earth's surface covered by ocean, satellites are a crucial element in collecting useful ocean colour data. Currently there are only a few instruments performing ocean colour monitoring around the world, operating aboard large satellites such as NASA's Moderate-resolution Imaging Spectro-radiometer (MODIS), with one of each on board the Terra (EOS-AM-1) satellite, and previously operational on Aqua (EOS PM). It has been unfortunate that a number of vital ocean colour sensors have been lost in recent years, particularly ESA's MEdium Resolution Imaging Spectrometer (MERIS) on board Envisat, and NASA's Sea-viewing Wide Field-of-View Sensor (SeaWiFS). SeaWiFS was launched on board the OrbView 2 satellite designed by Orbital Sciences (both pictured in Figure 1) in August 1997. SeaWiFS observed in 8 wavelengths across the visible and near-infrared (IR) regions with a spatial resolution of 1.1 Km. SeaWiFS could provide daily re-visits over specific areas, important for monitoring changes in oceanic health. Unfortunately in December 2010, after 13 years of successful operation, communications with the satellite came to an end.

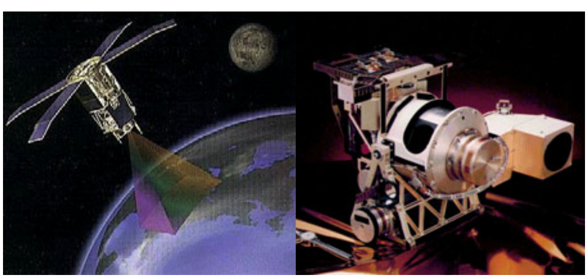

Figure 1- (Left) SeaStar illustration, (Right) SeaWiFS Instrument. Image Credit: http://oceancolor.gsfc.nasa.gov/SeaWiFS

Considering the lack of operating instruments, combined with the growth in demand for ocean colour data only capable of being collected through satellite observation, there is a clear need for further ocean colour space missions.

Sustained Ocean Colour Observations with Nanosatellites (SOCON)

Ocean colour instruments like SeaWiFS have proven to be extremely successful in supplying ocean colour measurements and monitoring global ocean colour, but their large pixels make measurements of lakes, rivers, estuaries, and the coastal zone difficult. Observation of these regions is important as much of the world's population lives in coastal regions. For the last few years a team of scientists and engineers, many of whom were part of the team responsible for delivering SeaWiFS, have been working to define and fund a mission that can satisfy the need for higher-resolution coastal and estuarine waters. A nanosatellite mission was of particular interest due to the low cost and rapid development timescales they offer. From these discussions the idea of using nanosatellites with integrated ocean colour sensors to emulate the SeaWiFS performance at higher resolution arose - and led to the development Sustained Ocean Colour Observations with Nanosatellites (SOCON) project, led by Professor John Morrison from the Center for Marine Science at the University of North Carolina Wilmington (UNCW). The goal of the project is to enhance the ability of the earth sciences to observe ocean colour in high temporal and spatial resolution modes, through the use of a low-cost, next generation, miniature ocean colour sensor flown aboard a CubeSat. To achieve this, two identical 3U CubeSats, named SeaHawk, will fly integrated miniature ocean colour sensors, referred to as HawkEye.

The SeaHawk platform will be provided by Clyde Space Ltd. With 10 years' experience, Clyde Space is one of the leading and most experienced designers of nanosatellites globally. With a focus on volume manufacturing of nanosatellites, approximately 40 spacecraft will be constructed at the Clyde Space facilities throughout 2015 and 2016, including the 3U PICASSO CubeSat for the European Space Agency (ESA). An Earth observation mission with a hyperspectral imaging payload, PICASSO is a baseline reference informing the SeaHawk platforms' similar design.

The design of the HawkEye ocean colour sensor is carried out by Cloudland Instruments, a highly experienced team and experts in their field, based in Santa Barbara, California. Specifically, the sensor optical design is led by Cloudland CEO Alan Holmes, who was previously a Systems Engineer for the SeaWiFS design. HawkEye is a multispectral sensor with spectral characteristics comparable to the 8 bands provided by SeaWiFS. The sensor is capable of collection of near-synoptic ocean colour data in open-ocean to coastal-margin to littoral to terrestrial environment, with a spatial resolution between 95-150m and swath of 250-400km in a 400-550km orbit.

The project officially kicked-off in April 2015. Currently the design is headed towards an expected Preliminary Design Review (PDR) in November 2015 with the Critical Design Review expected to be held around April 2016, depending on the outcome of the PDR. It is the aim of all members of the project team to have both CubeSats fully integrated, tested and ready for flight by 2017.

Moore's Law in Space

The funding for the SOCON project was provided through a grant from the Gordon and Betty Moore Foundation, which has a particular interest in SeaHawk from the perspective of technology demonstration, a "proof of concept" of a "game-changer" in the methodology of collecting and disseminating Ocean Colour Data via use of Nanosatellites.

Gordon Moore, who was also one of the founders of the Intel Corporation, is well-known as the author of Moore's Law, which refers to the trend whereby computer processing capability doubles every two years. The comparison between the previous SeaWiFS mission and SeaHawk & HawkEye is a cogent example of how the technological advancements driven by Moore's Law can be leveraged to deliver valuable scientific data from low-cost nanosatellites, on rapid development timescales.

The Orb View 2 spacecraft took more than a decade to develop, while the SeaWiFS instrument delivered a ground resolution of 1.1km. By contrast the HawkEye sensors – designed to operate within similar observation bands as SeaWiFS – will be produced in 2-years, and deliver a ground resolution of around 120m, whilst maintaining a Signal/Noise Ratio approximately 50% that of SeaWiFS. The CubeSat will be 530 times smaller (0.0034 vs 1.81m^3) with 115 times less mass (3.4 vs 390.0 kg), and all for a budget approximately 5 - 10% that of SeaWiFS.

2. MISSION AND SCIENCE OVERVIEW

The objective of this program is to demonstrate ocean colour observation in high temporal and spatial resolution modes, through the use of a miniature ocean colour sensor flown aboard a CubeSat. This system will have [illegible] that are poorly understood. High spatial resolution imagery will also improve our ability to monitor fjords, estuaries, coral reefs and other near-shore environments where anthropogenic stresses are often most acute, and where there are considerable security and commercial interests. Due to the low volume, mass, and particularly cost, it would become practical to fly constellations of these spacecraft, opening up opportunities to significantly improve temporal sampling.

In 2011, an ad-hoc study committee of U.S. National Research Council [1] convened to review the need to sustain global ocean colour radiance measurements for research and operational applications. They concluded "to support the goals and priorities outlined in the National Ocean Policy [2] and Ocean Research Priorities Plan [3] continued monitoring of the ocean's ecosystems on a global scale is essential. The continuity, global coverage, and high temporal and spatial resolution of ocean colour products make remote sensing a critical tool for monitoring and characterising ocean biology and marine ecosystems."

Ocean colour is one of the most useful remote-sensing missions to society, for both science and operations. Phytoplankton is overwhelmingly the largest contribution to primary production in the oceans and plays a vital role in the global carbon cycle. Present in all marine surface waters, their domain covers 71% of the Earth's surface, though their abundance can vary dramatically with location. The ocean colour community requires a broad and secure commitment for an integrated constellation of ocean-colour sensors to provide continuing ocean-colour data of the highest quality, thus ensuring that this capability will exist uninterrupted into the future: "Ocean colour provides our only window into the ocean ecosystem on synoptic scales. It is the sole method we have available to take a global view of the marine biosphere. Climate change is accelerated by the enhanced greenhouse effect, an increase in atmospheric carbon dioxide caused by the activities of man. We need to understand the processes that control atmospheric concentrations of carbon dioxide and other greenhouse gases. The Earth is a planetary system in which the land, oceans and atmosphere interact closely with each other requiring observing systems that show the linkages. The Earth's carbon cycle includes two-way flows between all three components - the role of the ocean is especially important. We are accustomed to thinking that to be Green is to be environmentally responsible and protective of the Earth. But the Earth is a Blue planet, three-quarters covered by water: we need to be aware of what is happening to both parts of the Earth's ecosystem, water as well as land. It is the aquatic biosphere that is monitored uniquely by ocean colour. The aquatic biosphere is under threat from global warming and ocean acidification. We want to know how it is responding to these and other perturbations" [4]

The more we observe the ocean on a synoptic scale, the more we realise that the processes we observe on global scales is replicated down to the smallest observable scale. Spatial heterogeneity, or ''patchiness,'' of marine phytoplankton populations is one of the oldest and most robust observations of open ocean biological oceanography. Structure is found in phytoplankton distributions at scales ranging from meters to the basin scale. At the mesoscale (1–300 km), structure in phytoplankton fields is often associated with physical features such as fronts and eddies. Meanwhile, our major long-term satellite ocean colour observations have been limited, and will continue to be limited in the near future, by available technology to scales of approximately 1 km^2.

3. TECHNICAL CHALLENGES

The Seahawk CubeSat is pushing the boundaries in what was previously thought capable with such tiny spacecraft. The most obvious challenge throughout the design is the extremely tight physical limitations for both the payload design and the CubeSat platform.

Power Generation

The current Concept of Operations (CONOPS) states that we expect the satellite to only observe during sunlight between specific limits, and that the CubeSat shall be capable of performing an observation once per orbit. This is a realistic – but challenging – requirement both in terms of power and data handling. Satisfying this drives a requirement to downlink within the same orbit, in order to avoid overloading the On-Board storage capability. Depending on the ground segment, this could imply a downlink opportunity on every orbit, i.e. both the payload and transmitter would be powered for periods of every orbit, placing an extremely large power demand on the satellite.

Data Handling

To obtain such high resolution and spectacular imagery, the expected data generation is immense. Over the course of a 100-second observation period, it is expected Hawkeye will be capturing hundreds of thousands of pixels every 0.01 seconds. This relates to a total raw data generation of 1.1 Gigabits for the full observation sweep. This is a significant volume of data; to help mitigate this data aggregation will be used to reduce the generated data to a more manageable amount. It is expected the CubeSat will typically be capable of downlinking the aggregated data files once per orbit, if the ground station is available. There are options to reduce the data handling requirement, such as expanding the ground segment, therefore increasing downlink opportunities, or reducing the observation period below 100s at times. In these cases the team would look to downlink the raw higher resolution data, if the power budget is favourable and if a lower observation period satisfies the science requirements.

Attitude Control

The need for fine pointing stability, and particularly pointing knowledge is extremely important. Obtaining high pointing stability will mean a smoother, more accurate image would be captured; however, due to the high resolution of the image, with insufficient position knowledge it will be difficult to determine the exact location of the observed area visually, particularly in the absence of any visible landmarks. Without this knowledge the scientific value of the data could be limited.

It is also important to consider the calibration requirements for the instrument. The main capture mechanism for HawkEye is a set of CCD linear arrays, therefore in order to maintain good image quality over time the effect of dark current must either be accounted for, or measures taken to reduce the effect. One such measure would be performing on-orbit calibration. The team is investigating the feasibility of performing a [redacted] in order to determine the dark current affects and account for this over time. This manoeuvre would require the CubeSat to fully rotate past the moon accurately enough capture the full moon image within the CCD array field of view.

4. SYSTEM DESIGN

HawkEye

Hawkeye is a small, 1U-sized instrument intended to measure ocean colour from low earth orbit. The intent of the instrument is to obtain performance comparable to SeaWiFS, but with higher resolution. The design will [redacted] with a ground resolution of 120 meters, for eight bands similar to SeaWiFS, during a single overpass ("sweep"). It will accomplish this by using 4 linear arrays, each with three 4080x1chroma channels, 10 micron pixels. Each array will sense two bands, with light focused onto each array by two individual F/5.0 triplet lens. Every lens has a band-defining interference filter. The three chroma channels for each array will be summed to improve the signal to noise ratio (SNR) of the result. The summing of the outputs increases the signal by 3X, and the noise by 1.7X, producing an SNR gain over a single array read of

1.7X. The arrays will also be read out 4 times during the time the instrument moves one pixel of ground distance, causing oversampling which in turn increases the signal to noise by another 2X. The oversampling enhances the dynamic range, so the instrument will sense light levels from the blue ocean to the sunlit cloud tops without saturation. 16 bit A/D converters will be used for each channel, and the aggregated result will be 12 bit, but with little noise. Double-correlated sampling will be used to reduce the reset noise of each array; a readout noise level of 25 electrons rms per read has been achieved in early testing.

The instrument will also use an area array CCD, with 648x486 pixels, under a separate short focal length (8.5 mm) lens, boresighted with the linear arrays. The purpose of this lens is to take a snapshot approximately every 400 lines of data, for use in later determining the direction of the motion of the scene across the linear arrays, allowing later resampling of the scene data to an orthogonal grid. We refer to this subsystem as the finderscope. At this time the finderscope has been included within the HawkEye design since it has not yet been determined if the CubeSat attitude can be known, after the fact, to within the 200 arcsecond accuracy required. The finderscope could work in conjunction with the CubeSat ADCS to achieve the precise attitude knowledge required.

It is anticipated that the CubeSat nadir-pointing direction will drift constantly at a slow rate. The finderscope array will determine the pointing direction and yaw angle every 10 seconds. If this proves not to be fast enough the array can be read out more often in orbit, with little impact on the total data volume. The linear arrays generate data at around 10.8 megabits per second (Mbps), and each frame of the finderscope is 2.5Mbit. Therefore one finderscope read every 10 seconds equates to 2% of the data volume. With the primary instrument arrays generating around 11 megabits per second of data for downlinking, over 100 seconds this accumulates to 1.1 gigabits of raw data – a large amount of data to downlink with current CubeSat capabilities. A combination of data compression and 2x2 binning of the data on orbit can be used to allow a good image to be collected in a single overpass while limiting the data generation. High data-rate downlink solutions are currently being investigated for the SeaHawk platform.

The HawkEye instrument will also contain a shutter. No instrument temperature regulation is planned, therefore the CCD dark current will vary considerably over time. The linear arrays will have a low level offset pattern that must be corrected, and the shutter will enable a dark frame to be captured at the beginning of a sweep. The dark data will then be subtracted from each array's data for the rest of the sweep. The shutter will also protect the CCD from inadvertent exposure to focused sunlight between scans. Although it is not known if the sun could cause damage to the linear arrays the expectation is that it could. By contrast the finderscope will not be affected by sunlight, since it uses an extremely small lens with an aperture <1mm and therefore, if required, it could be used to help establish CubeSat attitude control prior to collecting linear data. The dark current for this CCD is low enough that no shutter is needed. The linear array shutter will be a thin blackened metal sheet sliding on two rails. Solenoids fixed to the structure attach to the shutter sheet through a lever arm to uncover the arrays during a sweep. The translational movement will be only about 2 mm. In its non-energised state, a spring will hold the shutter in position to cover and protect the arrays. The drive mechanism is very simple, using redundant solenoids and springs to provide the actuation. Cloudland Instruments will work with Clyde Space to verify that the activation of the solenoid will not perturb attitude control significantly over the 100 seconds per orbit where it is energised. Figure 2 shows side on views of the instrument showing the optical path and various components discussed.

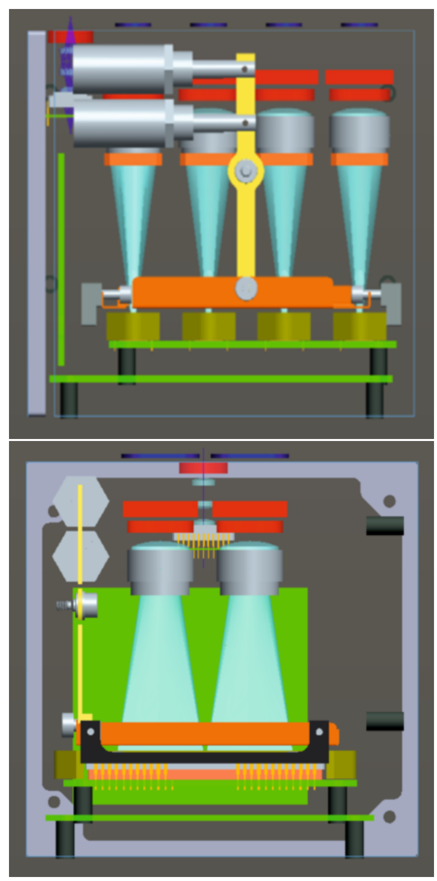

Figure 2 - Two side-on views showing the optical paths

In operation, the CCD arrays are first powered and take dark data, which is nothing more than 50 lines of data with the shutter closed. The shutter is then opened, and the linear arrays readout continuously. Every 625 lines of band data the area array is readout again (without interrupting the band data readout). At the conclusion of the data collection the shutter is closed. The CCD arrays and associated circuitry are powered down to save power while HawkEye's processor formats the data for downlink. The aggregation and accumulation of the 3 lines of data, oversampled 4 times, takes place in real time before storage of the data in non-volatile memory. The processor is well suited to this operation due to its FPGA component.

The optics, filters, and arrays will fit within the constraints of a $10cm^3$ unit, allowing for components of the CubeSat structure within this. Figure 3 shows the optics and CCDs mounted in the CubeSat envelope. Figure 4 shows the optics portion in a closer view; however, it does not show the baffles that will be necessary to confine the light from each lens to its associated array, and to suppress the out-of-field hemisphere of illumination striking the package.

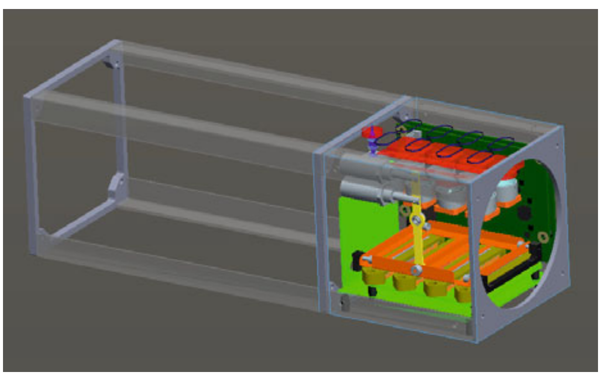

Figure 3 – The Optics and Detectors in a 1U section

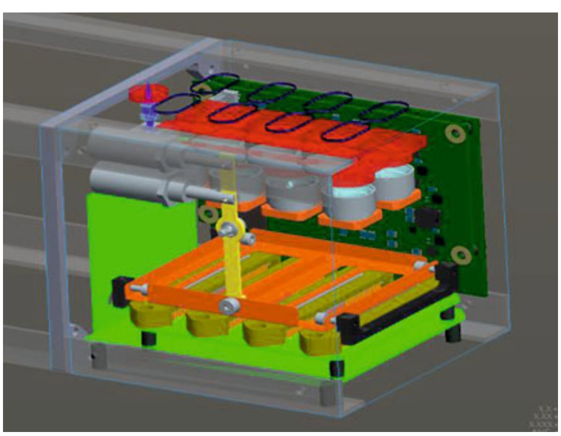

Figure 4 – Two bands are sensed for each array

We envision the baffle will be formed using a series of thin plates between the lens assembly and the arrays, with sharp edges defining the aperture within the interior. Stray light reduction is very important in this application, and will require blackening of lens edges and careful sizing of the optics to prevent the sunlit earth from lighting up internal structures near the optical path that can be seen by the linear arrays.

It will be challenging aligning 4 arrays to an accuracy approaching +/- 10 arcseconds (one half pixel). The CCDs cannot be rotated about their axis to make them coplanar after soldering, but the lenses will be translated in X and Y to achieve centring of each array's midpoint to a common reference. Ground equipment will be used to establish the final alignment of all arrays with each other and the finderscope array. We expect the array misalignments at the ends to be less than +/- 10 pixels.

The performance of this system to L-typical ocean colour radiance levels is shown in Table 1. This is for the full 1800 pixel, 120 meter ground resolution. Table 2 shows the 2x2 binned performance for 900 pixel wide data. The performance exceeds the SeaWiFS specification for Bands 1 through 6.

Table 1 – Chroma Array (10 Micron pixels, No binning)

Standard (Ltypical) Radiance			Radiance					**CubeSat**	SeaWiFS	Ratio,
Band	Wavelength	Bandwidth	Watts/m^2/	Optical	QE	Photons	Signal in	**SNR per**	SNR	CubeSat/
	in nm	in nm	ster/micron	Trans		per watt	Electrons	**pixel**	Spec	SeaWifs SNR
1	412	20	78.6	0.850	0.59	2.07E+18	20390	**487**	499	0.98
2	443	20	70.2	0.740	0.64	2.23E+18	18652	**465**	674	0.69
3	490	20	53.1	0.580	0.72	2.47E+18	13822	**398**	667	0.60
4	510	20	45.8	0.550	0.75	2.57E+18	12210	**373**	616	0.61
5	555	20	33.9	0.520	0.74	2.79E+18	9177	**321**	581	0.55
6	670	20	16	0.580	0.68	3.37E+18	5331	**239**	447	0.54
7	745	20	8.3	0.850	0.46	3.75E+18	3084	**175**	455	0.39
8	865	40	4.5	0.850	0.28	4.35E+18	2335	**149**	467	0.32

Table 2- Chroma Array (10 Micron pixels, 2x2 binning)

Standard (Ltypical) Radiance			Radiance					**CubeSat**	SeaWiFS	Ratio,
Band	Wavelength	Bandwidth	Watts/m^2/	Optical	QE	Photons	Signal in	**SNR per**	SNR	CubeSat/
	in nm	in nm	ster/micron	Trans		per watt	Electrons	**pixel**	Spec	SeaWifs SNR
1	412	20	78.6	0.850	0.59	2.07E+18	20390	**974**	499	1.95
2	443	20	70.2	0.740	0.64	2.23E+18	18652	**931**	674	1.38
3	490	20	53.1	0.580	0.72	2.47E+18	13822	**797**	667	1.19
4	510	20	45.8	0.550	0.75	2.57E+18	12210	**747**	616	1.21
5	555	20	33.9	0.520	0.74	2.79E+18	9177	**642**	581	1.11
6	670	20	16	0.580	0.68	3.37E+18	5331	**479**	447	1.07
7	745	20	8.3	0.850	0.46	3.75E+18	3084	**351**	455	0.77
8	865	40	4.5	0.850	0.28	4.35E+18	2335	**297**	467	0.64

The optical design is complete and the lens performance is excellent. A side view of the lens is shown in Figure 5.

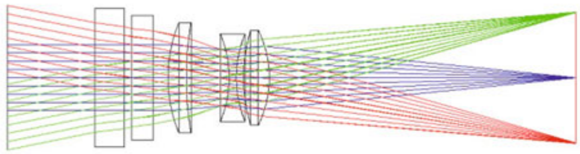

Figure 5 – Optical Layout

The lens focal length will be 45 mm with an aperture of 9 mm. The lenses will be custom, as will be the filters. The challenge for the filters is not the bandshape particularly, but the need to have excellent blocking of out-of-band radiation. This design should be excellent for stray light due to the simplicity of the optical design. The lenses will be antireflection coated. The arrays will be mounted without a window. These linear arrays do suffer from blooming at high signal levels, but this was investigated and it was found that as long as the light levels are below 1.6X saturation the blooming will not spread more than a pixel or two beyond the saturated pixels, while at levels of 2.0X saturation the blooming can corrupt pixels 180 pixels downstream of a saturated region's edge, along the array.

The three sensitive chroma arrays for each band are spaced 9 pixels apart, so to avoid blurring of the final image formed by summing separated arrays the CubeSat must align the array perpendicular to the velocity vector to an accuracy of about +/- 3 degrees (at full resolution). For 2x2 binned operation this relaxes to +/- 6 degrees.

Polarisation sensitivity has been investigated and the linear arrays were found to have a variation of +/- 3% in sensitivity with polarisation at normal incidence. This was surprising but may have something to do with the CCD structures being comparable to the wavelength of light. To reduce this sensitivity further a single quartz prism depolariser will be added to each band in front of the filter. This will reduce this sensitivity to below +/- 0.5%.

A once-per-month lunar calibration will be possible by rolling the CubeSat view past the moon. This will help track changes in the absolute calibration. Linear arrays also have pixel-to-pixel variation of about 0.5% in sensitivity that can be calibrated using flat fields or sphere sources during ground testing. Changes during orbit should be minimal, and any image striping that develops correctable based on data with uniform scenes.

Assembly and test of the two units contracted will be performed in 2016, with delivery late in the year.

Power System

The SeaHawk power system is composed of a number of Clyde Space COTS components which together provide all power provision, protection, distribution and conditioning means for the CubeSat sub-systems and the HawkEye payload module. The main components to make up the power system are the EPS board, battery secondary power source and a combination of high-performance solar panels. The EPS chosen for SeaHawk is the Clyde Space Third Generation FlexU EPS, an Off-The-Shelf subsystem specifically designed to support high-power CubeSats with deployable solar panels. A FlexU EPS is displayed below in Figure 6

Figure 6 - Clyde Space FlexU EPS Board.

The FlexU EPS provides three regulated primary power lines – 3.3V @ 4.5A 5V @ 4.5A, 12V @1.5A – in addition to an unregulated battery line at 4.5A, and provides 10 Latching Current Limit power distribution switch channels. Battery Charge Regulators (BCRs) with Maximum Power Point Tracking (MPPT) consistently optimise power generated from the solar panels. The FlexU EPS also provides protection for the spacecraft against power bus over-current, and battery over- or under-voltage events, as well as featuring a watch-dog timer to reboot the system for error recovery in case of unforeseen events. The Clyde Space EPS range has significant heritage, with an appreciable fraction of all CubeSat missions being powered by a Clyde Space EPS.

The secondary power source selected for SeaHawk is the Clyde Space Third Generation 30Whr standalone battery. Initial analysis shows this battery configuration should provide enough power to operate the relevant systems in eclipse, and exhibits good depth of discharge characteristics. Based on Lithium Polymer technology, the battery cells are arranged 2S3P, with charging EoC voltage of 8.2V.

At this stage of the project the solar array configuration is still to be finalised, pending further analysis. However, a flower arrangement similar to that displayed in Figure 7 with double sided panels is one of the promising configurations currently under consideration.

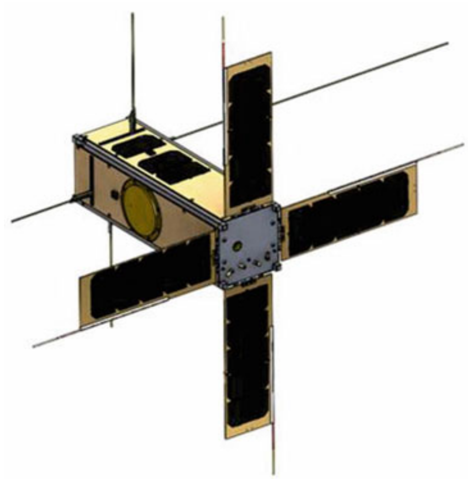

Figure 7 – CAD rendering of the PICASSO CubeSat currently in development by Clyde Space, ESA and the Belgian Institute for Space Aeronomy.

It is expected the HawkEye payload, the most power intensive system on-board, will be operated in sunlight with science acquisitions taking place between 10 AM to 2 PM local time, but never closer than 15 degrees to or from the terminator. This, along with power consumption, is a significant consideration in the design of the solar arrays in order to either maximise the amount of power available at the highest point of power consumption, or ensure that the batteries are fully charged before entering the eclipse period.

Attitude Determination and Control System (ADCS)

There are a number of challenges associated with the attitude determination and control of the SeaHawk CubeSats. Previously, Earth Observation missions using CubeSats have often been dismissed as it was thought that they would not be capable of providing the strict pointing accuracy and control required for earth observation applications. For Seahawk, the priority lies in obtaining the pointing knowledge and fine control, rather than an intensely-high pointing accuracy. It is expected the platform CubeSat must obtain a pointing accuracy of at least +/- 3° in all axes whilst maintaining adequate stability and minimising any jitter throughout the system, with a target of +/- 1° in order to reduce the load on the payload target correction capability.

A particular challenge for Ocean Colour Monitoring missions such as SeaHawk is the need to avoid sun glint off the ocean while observing. This places further constraints on the attitude control system, requiring the capability to pitch the spacecraft at intervals of 5° between 0 and +/- 20°.

SeaHawk's ADCS will consist of a range of sensors and actuators listed below,

- Clyde Space ADCS Motherboard
- Clyde Space 3-Axis Reaction Wheels
- Single Axis Coarse sun sensors
- 2-Axis Fine Sun Sensors
- Three Axis Magnetorquers
- Magnetometers
- Rate Gyro Sensors

The ADCS motherboard, displayed in , benefits from the heritage of the ADCS board that has successfully flown on UKube-1. An FPGA-based processing architecture has been specifically selected to ensure a system that is more robust to radiation events. The central Actel FPGA interfaces to the sensors and actuators, while a secondary processor acts as a watchdog, can place the spacecraft into a safe mode and can also be used to provide emergency detumbling of the spacecraft should the need arise.

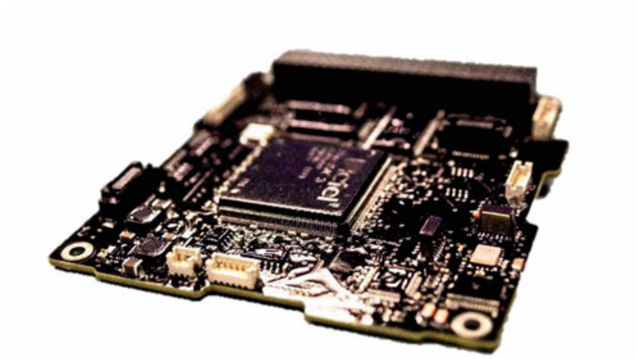

Figure 8 - Clyde Space ADCS Motherboard

The ADCS will utilise the standard Clyde Space three-axis CubeSat reaction wheel system, depicted in Figure 9. Each reaction wheel is capable of providing a torque of up to 2mNm. The wheels will provide a total angular momentum of 3.53 mNms, with an angular velocity range of ± 7500RPM.

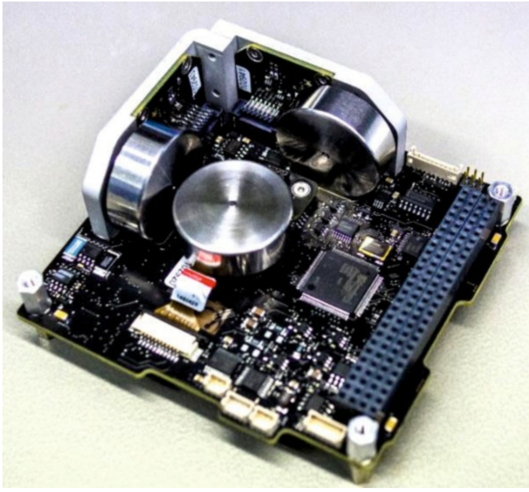

Figure 9 – Clyde Space 3-Axis Reaction Wheels

As previously mentioned, the CubeSat may be required to perform a lunar calibration to account for dark current effects in the HawkEye CCD arrays. It is expected that the lunar calibration could be performed by spinning the reaction wheels to send the CubeSat into a full 360° pitch rotation, which at some point the moon will be captured within the payload view. The important thing is to maintain the correct pitch rate to ensure the image captured from the CCD readout is not overly skewed. It is expected this will be achieved through the use of the 3-Axis Reaction Wheels.

The ADCS is validated during ground testing using Clyde Space's Hardware-In-the-Loop (HIL) simulator. The complete HIL set-up is a high fidelity, six degrees of freedom, spacecraft dynamical model interfaced directly with the ADCS hardware on which the attitude control algorithms run. The set-up allows validation of the autonomous attitude control software and hardware for all phases of the mission.

Voice coils embedded into the solar panels represent the magnetorquers (MTQ). These devices generate a magnetic dipole that interacts with the Earth's magnetic field, generating a mechanical torque. These actuators are used to de-tumble the spacecraft, to provide coarse pointing acquisition, and to manage the RWS angular momentum.

Critically, real data from the sensors and actuators will be used to simulate the entire mission. This allows many of the un-modelled dynamics that, because of the presence of unknown parameters, do not have clear mathematical formulations. These can include interference on the magnetometers from magnetorquer output and magnetometer reading; reaction wheel velocity and gyros output; sensor noise and pointing accuracy; and others. Consequently, the use of this system level HIL test vastly reduces the impact of 'non-ideal' operation of system hardware on the performance of the ADCS control algorithms, and therefore de-risks the potential for attitude control problems on-orbit.

Communications System

The communications system consists of two hardware components, a transceiver for TM/TC communication and a high data-rate transmitter specifically dedicated to downlink payload data. Telemetry and Telecommand communications are performed by a dedicated UHF/VHF transceiver, the CPUT VUTRX CubeSat transceiver. The VUTRX implements half-duplex GMSK and AFSK modulation schemes with data rates of 9600 and 1200 baud respectively using modified CCSDS packets. The transceiver also features a Beacon mode to broadcast identification and basic health data for tracking, particularly useful when the CubeSat enters the initial separation, de-tumbling or standby mission modes. The VU Transceiver interfaces to a combination of dual UHF and VHF omnidirectional Whip Antennas deployed from the Antenna Deployment Module (ADM).

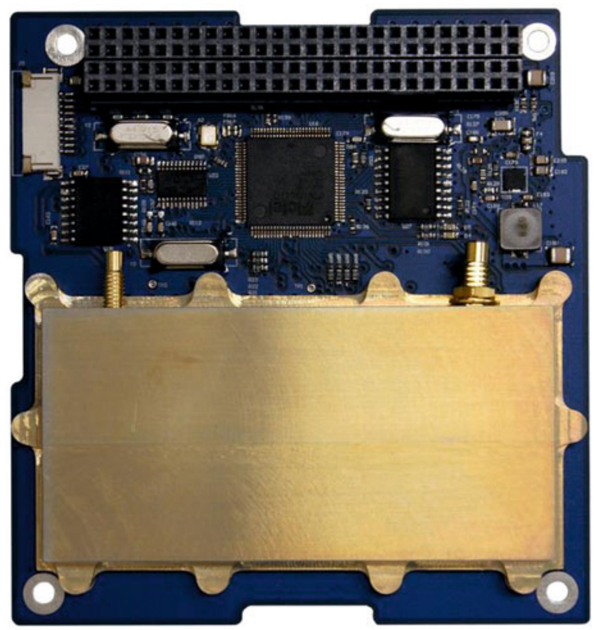

Figure 10 – CMC VUTRX CubeSat UHF/VHF Transceiver

The science data downlink communications system has yet to be finalised. Initially an S-Band downlink solution was baselined; however, it soon became apparent that this mission would generate a large amount of data, meaning other options must be considered in order to maximise the downlink capabilities. Currently the team is investigating a number of options and trade-offs including data aggregation techniques, ground segment configurations and various operational considerations to determine a way to work around the possible issue. The team is also examining a possible move to an X-Band downlink solution. However, due to the higher power consumption and larger physical characteristics of an X-Band transmitter, this would put a large demand on the system design. These trade-offs will be analysed intensely over the coming months and it is highly expected this decision will be resolved following discussion at the PDR.

Command & Data Handling

SeaHawk shall have two separate data flows, one for science data and the other for Telemetry and Telecommand data. Both data streams will be routed through two different interfaces. The science data must be transferred from the payload to the On-Board Computer (OBC) within a matter of minutes to ensure the high-power payload can be powered down as soon as possible. This calls for a very high data rate interface; the team is currently investigating the available options before finalising their choice. For simplicity, and also due to power requirements, it has been decided to proceed without a fully dedicated payload computer to store and transfer payload data, instead all data will be transferred and routed via the OBC.

As discussed earlier in this paper the payload has an extremely large data generation. The raw data will be saved, and then aggregation performed to reduce the amount of data required for downlink whilst still maintaining good image quality. The team is investigating implementing a binned mode for the payload data collection, such as 2x2 binning, to further reduce the data generation if required.

On Board Software

The platform OBC runs the Bright Ascension Generation 1 On-board Software. This component-based software has an underlying framework including OS and hardware abstract libraries, as well as support for FreeRTOS and POSIX/Linux. The software components support CS platform subsystems including integrated EPS, Battery, solar panels, ADCS, VUTRX and the standard CS payload protocol. Activities including telemetry sampling, pooling, monitoring, logging, etc., as well as automated activities that are event-, time- or orbit-triggered are also supported.

Structure

The structure used will be the Clyde Space standard 3U CubeSat structure featuring custom cut-outs for payload apertures and mounting requirements. The standard structure has been designed specifically with design flexibility in mind, allowing a range of CubeSat stack and payload configurations to be easily designed and implemented within the confines of the structural components. A Clyde Space 3U structure is depicted in Figure 11.

Figure 11 – Clyde Space 3U Structure

An interesting structural requirement is the provision of a one-time door, something more typical of larger earth observation spacecraft. The door will be used to cover the sensitive optics during launch and the initial tumbling phase, ensuring the optics will never face the RAM direction or direct sunlight while unprotected. A solution currently being investigated is simply to use a deployable PCB panel as the door, utilising Clyde Space's existing solar panel deployment technology which has successfully flown on multiple missions previously. This will cover the payload face when stowed and deploy following successful de-tumbling. While stowed, the payload face will not be sealed, there may be a few millimetre of clearance between the panel face and the payload aperture, meaning the payload aperture would still be susceptible to the space vacuum environment. Therefore another purpose of the one-time door would be to allow any substances, such as oil, which may have condensed onto the lenses during the launch procedure to outgas before the payload face is subjected to any light.

5. SUMMARY

Ocean Colour Monitoring provides valuable scientific data which can be used worldwide, not only by scientists to fulfil important research but also by commercial businesses who operate on and rely on the health of our marine biosphere. Currently there is a need to develop a capability to produce high resolution ocean colour data on a global scale, something only possible by satellite observations. The SOCON project aims to bridge this gap using miniaturised push-broom CCD imagers integrated within two 3U CubeSats.

The HawkEye sensor will generate data in 8 wavelengths, very similar to the SeaWiFS observation bands, with a spatial resolution between 95-150 m. The amount of data generated by HawkEye is expected to be around 0.65 GB after aggregation, which places a large demand on the communications and data handling systems of the SeaHawk platform. In order to obtain the highest quality data, there are specific manoeuvrability requirements placed on SeaHawk. This includes the need to perform lunar calibration, accounting for dark current in the HawkEye CCD arrays, and discretised pitch manoeuvres to avoid sun glint off the ocean surface. The SeaHawk ADCS design is tailored, in both hardware and software capabilities, to perform these manoeuvres.

Successful demonstration of this mission will be ground-breaking for both the nanosatellite and ocean colour communities. Proving that the required high resolution optical performance can be achieved using a sensor designed to such tight physical and electrical limitations in itself is a huge success. If it can then also be proven this sensor can be successfully operated and integrated to such a low cost platform, this will open up a vast range of opportunities for ocean colour monitoring using smaller satellites and hopefully lead to an increase in the amount and type of ocean colour data available. A key goal of the SOCON project is to open the door to constellations of dozens of satellites utilising the SeaHawk design, providing more detailed information on our oceans than has previously been possible.

More generally, the lessons learned from this nanosatellite design will contribute to future platforms and will be yet another advancing step in nanosatellite capabilities. Showing that nanosatellites can compete with larger satellites and can provide opportunities which don't currently exist will push the reputation of CubeSats as Earth Observation platforms forward.

6. ACKNOWLEDGEMENTS

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