CEOI Challenge Workshop
Emerging Technologies for EO Instrumentation

3rd May/4th May 2017
Cosener's House, 15-16 Abbey Cl, Abingdon OX14 3JD

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1 Introduction and aims

On 3rd and 4th of May 2017, we held another of our biannual Emerging Technologies Challenge Workshops (ETCW) at Cosener's House, Abingdon, Oxfordshire. This is the first of the ETCW meetings to be held under the new CEOI contract and reflects the situation as we build momentum in this new phase. We had around 60 delegates attending over the two days, including several attendees from ESA and the UK Space Agency. The purpose of the meeting was to:

- Review the technologies arising from new and ongoing CEOI project work;
- Encourage collaboration among the academic and industrial groups attending;
- Expose emerging instrumentation concepts to the science community;
- Examine opportunities for wider applications of emerging EO technology;
- Contribute to the evolving UK strategy for EO and EO technology;
- Hear about technology needs from national and international stakeholders;
- To look ahead to more exotic technologies that might feature in future EO instrumentation.

In this meeting, we had a varied agenda with talks on topics of current interest including:

- CEOI Technology in missions, both current and future;
- Miniature systems;
- CEOI and UKSA plans for the next 3-5 years;
- Innovative microwave and Radar developments;
- Detectors
- International perspectives;
- Future trends.

1.1 CEOI Technology in Missions

Over the 10 years of the CEOI, we have seen a number of CEOI sponsored technologies carried on spaceflight opportunities, or at least do very well in the ESA and Copernicus mission competitions. More recently, there have emerged a number of commercial mission opportunities in which there is tighter coupling between CEOI projects and a direct national or export spaceflight opportunity. ESA remains a key target for the UK, and with the strong investment from the UK into ESA EO activities, we must maintain an edge in EO instrumentation in order to capitalize on the UK's dominant position.

We report on successes in deploying CEOI sponsored GNSS reflectometry instrumentation from SSTL into TechDemoSat and on the NASA CYGNSS 8-spacecraft constellation which will monitor tropical wind, storm and sea state. We also examine CEOI sponsored work for:

- The SEASTAR Earth Explorer candidate, a SAR-based precision wind, wave and ocean current mission, under study by the national Oceanography Centre and Airbus Defence and Space;
- TRUTHS, an optical imaging radiometer carrying an advanced calibration payload which will provide gold standard calibration for climate measurements, currently in an advanced breadboard state in NPL.
- A low-Cost EO imager for a commercial constellation, currently under construction at SSTL. 8 Optical payloads will be required in due course to complete the 16-satellite constellation.

1.2 Miniature systems

There is considerable interest in reducing the size, mass and power consumption of instrumentation payloads, to reduce the overall mission costs. What we have found is that smaller size can be achieved using different approaches, and that small does not mean poorer performance in all cases. In principle miniaturisation allows:

- Lower launch, and therefore lower mission costs;
- Smaller spacecraft, including cubesat platforms, to host scientifically and commercially useful payloads;
- New payload configurations, using multiple instruments;
- Affordable constellation concepts, allowing important science and powerful applications to be realized at low cost.

In this session we heard about:

- Small laser sources under development at the Fraunhofer institute in Glasgow;
- Progress in development of the microchip resonant cavity spectroscopy concept from Zinir;
- New MEMS level spectrometers for atmospheric remote sensing from microsat platforms;
- The potential of cubesat platforms for EO missions – from Clyde Space in Glasgow;
- New single pixel techniques for very small imagers and spectrometers.

1.3 CEOI and UKSA strategy discussion

The CEOI has been performing a capability and gap analysis on UK organisations in a bid to shape a new instrumentation strategy that is currently in development. In this session the emerging CEOI strategy was outlined alongside UKSA plans for EO for the next few years. The delegates were invited to ask questions, make comments and offer suggestions.

1.4 International perspective

The second day kicked of with an invited talk from Massimiliano Pastena, who is a member of the Future EO Missions team at ESA ESTEC in the Netherlands. Of particular interest were ESA and EU plans for future Copernicus missions.

1.5 Innovative microwave and radar concepts

Returning to the specific technologies theme, recent developments in radar, including imaging SAR and Doppler radar for cloud remote sensing were discussed. In addition, passive microwave techniques for coastal altimetry, and atmospheric chemistry sounding were explored. In particular:

- The commercial NovaSAR low-cost SAR mission was described, along with progress updates from Airbus Defence and Space;
- Progress on the CEOI-supported 94GHz Doppler radar for the ESA WIVERN Earth Explorer mission candidate was reported by the University of Reading;
- New THz sounders for sounding of the upper atmosphere, using the latest quantum cascade laser local oscillators, were described, along with applications to the LOCUS ESA Earth Explorer mission candidate were described by RAL Space.

- A new resonant filterbank spectroscopy technique for atmospheric chemistry sounding was described by the University of Cardiff.
- A new requirement and passive microwave radiometer concept in support of coastal radar altimetry was described by JCR Systems.

1.6 Detectors

A regular feature in the ETCW meetings is a review of the latest developments in detector technology for all parts of the EO spectrum of importance to Earth observation. The meeting showcased:

- New Quantum Cascade Lasers for use as local oscillators in IR, Microwave and THz receivers from the University of Leeds;
- Other microwave and THz detection techniques from the University of Cardiff;
- The latest developments in IR detectors (NIR, SWIR and TIR) from Leonardo;
- New developments in optical imaging detectors from Teledyne E2V.

1.7 Future Trends

This session is the embodiment of the CEOI horizon scanning activity, which looks ahead at new techniques, which may be theoretical or low TRL laboratory techniques at present, but may offer powerful solution or EO in the future. The session kicked of with RAL describing the future plans for development of the AIV facilities in the new R100 building at Harwell. The new facilities are designed to support the growing space community in the UK. New techniques explored included:

- Novel techniques in optics including optical meta-materials , were outlined by Leonardo (Edinburgh);
- A study of Ku-band microwave radiometry of the polar atmosphere, described by British Antarctic Survey;
- Innovative materials for deployable systems as described by Oxford Space Systems;
- Novel applications of cold atom interferometry for gravity field measurement from space.

Most presentations are available on the CEOI website, and the proceedings and many of the presentations for prior meetings are also available.

http://ceoi.ac.uk/

2 The presentations - Day 1: 3rd May 2017

2.1 Introduction

Mick Johnson & Chris Brownsword*, Director of the Centre for Earth Observation Instrumentation and CEOI Technology Director respectively*

Mick introduced the objectives of the meeting and gave a brief overview of the CEOI activities since commencement of the new CEOI management contract in October 2016. He also described the review of the CEOI programme, which was chaired by David Southwood, which gave a very positive endorsement of the programme and its methodology.

Mick reminded the audience of the current EO landscape, including the UK becoming the largest subscriber into the ESA EOEP 5 programme, thus giving technologies for ESA a higher priority. The evolution of Copernicus and the emergence of new commercial opportunities are supported by the UKSA strategy to link upstream technologies to downstream services.

CEOI remains focused on strengthening UK EO technology capability, with enhanced breadth and depth, and this will be achieved by:

- Organising technology calls and community events to strengthen academic/industry partnerships;
- Funding of innovative technologies for global EO mission opportunities;
- Providing support for developments for commercial exploitation opportunities.

In this way CEOI will maximise leverage of investment in EO from industry and elsewhere to create new UK jobs and economic growth.

The added value programme has been streamlined to place more emphasis on engagement with ESA and other international agencies, but the programme will continue to:

- Build technological communities and capability, encouraging academic and industrial collaboration via community events, Challenge Workshops and engagement with international stakeholders;
- Disseminate information to and among the wider EO community, in particular with respect to ESA and Copernicus programmes.
- Encourage technology transfer via technology showcases and industrial engagement, to stimulate maximum economic growth;
- Provide publicity for the UKSA funded EO technology programme.

Mick described the positive outcome of a recent ESA engagement meeting at ESTEC and outlined the plans for the CEOI programme for the rest of the year.

Chris Brownsword gave an overview of progress on the current Open Call, and a brief summary of progress on current major projects. He also provided a summary of lessons learned in the recent calls, which also included feedback from the review panel of the last call. This material will inform our next Open Call and will be used to brief prospective bidders.

2.2 Pathways For Broader Exploitation Of EO Technologies

Robin Higgons*, QI3*

Robin summarized the CEOI Industry Engagement programme from its beginnings in 2008 to the present. Robin noted that more CEOI technologies are moving up the TRL ladder, from the early days of TRL 3 towards TRL 6/9.

He summarized the QI3 methodology for evaluation of the broader technology exploitation, which is based upon a well established framework. For exploitation, QI3 consider terrestrial and embedded remote sensing for e.g. hazardous environments in addition to space-based remote sensing. Robin outlined some known application areas, which can be addressed by EO sensors. The Knowledge Exchange programme, now in its 5th Phase, divides naturally into two branches:

- Broadcast activities involving general exhibitions and events, and
- Targeted activities where specific communities and/or application domains are engaged.

It was noted that the CEOI website allows organisations to 'shadow' CEOI technologies. Organisations may become commercially interested when the technology is mature and/or when the market is receptive. One of QI3's major goals is to encourage and amplify this effect.

3 CEOI Technologies in Missions

3.1 GNSS Reflectometry for Global Ocean Wind Monitoring & Services

Christine Gommenginger (Spkr) & 3 Others *National Oceanography Centre*

Christine outlined the successes of the SGR-ReSI GNSS reflectometry instrument currently flying on board TechDemoSat-1 (TDS-1), and which has been recently embarked upon the NASA CYGNSS satellite constellation. She also considered the options for future exploitation of GNSS reflectometry.

The TDS-1 flight has allowed the collection of the world's first global data set of GNSS reflectometry data, and provided an opportunity to thoroughly explore the instrument calibration, performance of the instrument, and to develop the ground processing methodology for maximum benefit. The instrument measures wind speed to almost ~2m/sec, and has coverage and accuracy comparable to ASCAT. The TDS-1 flight has also allowed optimization of the instrument concept, and provided flight heritage, which enabled SSTL to capture the CYGNSS export opportunity.

Another world first is the first GNSS reflectometry measurement from a hurricane, which provides an excellent proof of concept for the CYGNSS mission. CYGNSS was launched in December 2016 and is providing global wind data from a constellation of 8 microsatellites deployed in a single orbital plane. The constellation has been operational since March 2017.

For the future, NASA has plans for a CYGNSS 2 mission, and ESA are studying the ORORO mission concept in which up to 30 satellites could be deployed.

3.2 SEASTAR: A New Satellite Mission Concept To Observe Sub-Mesoscale Ocean Surface Currents & Atmosphere/Ocean Coupling

Christine Gommenginger (Spkr) & 4 Others *National Oceanography Centre*

The ocean is dominated by motion at the meso- and sub-mesoscale (10-100Km down to 1-10Km). These features can be seen in sea surface temperature imagery, but there is scarcity of data on dynamics at these scales. Measurements are needed to understand upper ocean dynamics and atmosphere ocean coupling to improve ocean and climate models.

SEASTAR is a SAR mission concept, which will deliver 2D maps of total ocean current and wind vectors at 1km resolution. It will enable the study of important small-scale phenomena in the coastal zone, the Arctic, and specific sites of scientific interest. It will improve validation of ocean and atmosphere modeling, and assist in improvement of paramaterisation.

Christine described the current SAR instrument concept. The proposed mission uses single platform, single pass interferometry with forward and aft focused beams. Each scene is viewed from two azimuth angles to derive the motion vectors. It is clearly a large mission and a candidate for an ESA Earth Explorer Core class mission, with a ROM cost of around €250M.

An airborne campaign is being used to validate the concept, and algorithm development is maturing. Accuracy of vector retrieval is good, but is very sensitive to wind direction with respect to the flight path. A 3-look concept is under investigation, which it is hoped, will mitigate the wind direction issue.

3.3 Lo Cost Imager For EO

Ryan Kraliz *SSTL*

SSTL are developing a new imager payload for an overseas commercial customer. The system features a Cassegrain telescope and a focal plane assembly, which will deliver sub-1m resolution still images via the push-broom detectors, and 4K (UltraHD) video. The imager will operate in a constellation of small satellites, which will maximize the opportunity for cloud-free operation.

In addition, SSTL is developing associated technologies to allow Near Real Time (NRT) delivery of data, and this includes on board storage, processing and inter-satellite communication systems in addition to the necessary ground processing concepts. The UK positioning will also allow preferential access to UK downstream data for researchers and applications developers.

With CEOI support, SSTL are building a flight representative breadboard ahead of building the full flight instrument.

3.4 TRUTHS - Technology Demonstration

Lydia Zajiczek *NPL*

TRUTHS is an imaging radiometry mission concept to provide Standards Institute grade calibration for full SI traceability of measurements in support of climate studies. The mission will measure Total Solar Irradiance and Earth Spectral Radiance with unprecedented accuracy for climate benchmarking. In addition, it will provide validation of existing and future EO satellites via cross calibration.

There are three main elements:

- Cryogenic Solar Absolute Radiometer (CSAR);
- Hyperspectral Earth Imager (EI);
- Calibration system: calibrates EI with CSAR via transfer radiometer.

The project is at the 'elegant breadboard' stage in which the full instrument has been built in a space representative manner, allowing full evaluation of the likely performance of the flight configuration.

The CSAR provides SI traceability of the Earth Imager (EI) calibration and TSI measurements as a "primary standards laboratory in space", using the electrical substitution method:

- A ground-based CSAR is currently based in Davos, Switzerland (a future SI standard for solar irradiance);
- Recent work involved updating terrestrial design to more space appropriate design and ensuring compatibility with Airbus Defence and Space's High Performance Stirling Cooler (HPSC).

The main components of the calibration system are:

- An array of single-wavelength, power stabilized laser diodes (Range 350 nm to 2300 nm)
- Beam delivery optics, featuring a fibre combiner, collimator, and a rotating prism arm
- Transfer radiometer (calibrated with CSAR), featuring an integrating sphere with two detectors (Si and InGaAs), and an external aperture to define radiance
- A Spectralon diffuser disk (viewable simultaneously by TR and EI) and illumination optics, featuring an Illuminating sphere, collimating lens, steering mirrors.

The breadboard is operating well and is showing that the mission concept is achievable. The speaker outlined the future steps to a fully space qualified calibration system.

4 Miniature Systems

4.1 Laser Source Development At Fraunhofer CAP For Lidar, Remote Spectroscopy And Space-Based Quantum Technologies

***Loyd Mcknight**, Fraunhofer Institute UK*

Loyd described the philosophy of the Fraunhofer Institutes, and in particular their role in the UK. The motivation is similar to that of the Catapult Centres. Like the Catapults, it is a not-for profit organisation, but Fraunhofers operate bottom-up, by embedding within a university to develop technologies, and to derive commercially viable products from them. The Fraunhofer Centre in Glasgow is one of 70 institutes worldwide (60 in Germany), pursuing demand driven research supported by scientific excellence.

The Fraunhofer Institute in Strathclyde University in Glasgow addresses research, engineering and design in the following areas:

- Solid State Lasers;
- Mid Infrared Lasers;
- Semiconductor Disk Lasers;
- Integrated Optics;
- Modeling, designing and prototyping;
- Instrumentation.

These disciplines address a variety of market segments including:

- Emerging and Enabling Technologies.
- Infrastructure Systems.
- Health and Life sciences.
- Manufacturing and Materials.

The Fraunhofer CAP in Glasgow addresses many technologies that are directly or indirectly related to Earth observation. In particular integrated optics resonates strongly with the CEOI pus towards instrument miniaturization. To this end, Fraunhofer could be a highly appropriate partner for future CEOI collaborations, with powerful routes available to address potential spin out markets.

4.2 Development Of A SOLO Spectroscopy Gas Sensor In The Mid-IR

Stephen Sweeney, *Zinir*

Current spectrometers use prism/grating dispersion, Fourier Transform interferometers, or heterodyning to achieve high spectral resolution, and while each approach has advantages, there are drawbacks including large size, high mass, moving parts and complexity. The Zinir SOLO resonator-based solid-state microchip device could be enabling for miniature EO spacecraft applications such as spectrometers and hyper-spectral imagers for cubesats.

The microchips can be built with cavities tuned to specific wavelengths of interest, and the resulting chip die is millimetres in size. This allows volume production, and in due course, relatively low cost. Deployment of arrays of devices is feasible for hyper-spectral imaging.

Optical wavelengths to 3µm are possible using an approach already protoyped by ZiNIR, and with GaAs/AlGaAs semiconductors and an intraband based approach, up to 15µm should also be achievable.

Zinir are currently focusing on detailed device design and prototype manufacture.

4.3 Miniaturized High Performance Spectrometers For Microsat Atmospheric Mission

Damien Wiedmann, *STFC RAL Space*

The motivation for miniaturization to access small satellites is compelling and allows:

- Potential low-cost systems
- A rapid development cycle
- Heritage building
- A less risk averse culture
- Hands on training
- A lower barrier to entry for small businesses.

Damien examined several miniature spectrometer concepts, including his own Laser Heterodyne Radiometer, (LHR) and emerging technologies such as MEMS-based spectrometers.

The LHR is a maturing concept featuring very high spectral and spatial resolution in the mid-infrared with modest optics, and the basically simple configuration allows a number of miniaturization routes including:

- Miniature components
- Hollow waveguide
- Metal waveguide
- Laser inscription waveguide

Damien described the MISO (Methane Isotopologues by Solar Occultation) mission project with the University of New South Wales. MISO is solar occultation limb sounder which will be embarked on a 6U cubesat, to study the methane budget, gas transport and life cycle.

Damien is investigating the potential of MOEMS miniature spectrometers. These are produced using the techniques of the semiconductor industry, and therefore can in principle be mass produced for low cost. Silicon is transparent in the short wavelength infrared, and is compatible with device integration via waveguide. Miniature FTIR devices are available as well as miniature grating spectrometers. With CEOI Pathfinder support, Damien is investigating CO_2 and CH_4 spectroscopy (12nm resolution in the 1-2.5μm band). He is also investigating the potential for space qualification, including temperature stability and robustness against shock/vibration.

These miniature devices are potentially very enabling for small satellite and cubsat deployments, and lend themselves to low-cost In-Orbit Demonstrators (IODs). The Thermal Infrared (TIR) LHR and SWIR MOEMS FTS are compatible with the size and power constraints of these small missions, and offer strong capability/cost ratios. In addition to EO these devices are enabling for low-cost planetary missions.

4.4 Cubesat Capability – Enabling EO Mission Cost Reduction

***Alasdair Gow**, Clyde Space Limited*

ClydeSpace are the main provider of cubsat technology in the UK, and they are seeing growing take-up, as new highly capable miniaturized payloads become available. Thus cubesat plaforms, in both the classic 3U and larger 6U, 12U configurations, are increasingly a target for CEOI and the EO community.

As demand grows, so does the potential for cost reduction by mass production of reliable platform components. With an order book approach treble figures, the trend is likely to continue. Clyde have seen a price reduction of (average) 25% despite a staff increase of 40% over the same period. Clyde supply the following COTS sub-systems for cube and other small satellite platforms:

- Power Systems: EPS, Batteries, Deployable Solar Panels
- Attitude Control: Processing units and algorithms, reaction wheels, thrusters
- On-Board Computers
- Structures
- Partners: Comms, software, sensors

Alasdair described (among others) the SeaHawk mission, which currently comprises 2 Clyde Space 3U cubesats carrying the HawkEye ocean colour payload as a technology demonstrator. The performance is expected to be better than that achieved by the original SeaWifs OCM sensor, and once proven will replace it. Alasdair also described the Satellite Applications Catapult IOD Pilot Programme.

Finally Alasdair described some of the emerging technologies under development at Clyde Space.

4.5 Single-Pixel Camera For Remote Sensing

***Wojciech Roga**, Strathclyde University*

Wojciech described to progress on an NSTP3 Pathfinder project to investigate a compact multispectral imager for nano-satellites. The technique uses a single pixel sensor and an image encoding scheme to achieve high image compression ratios, with acceptable image fidelity. The imaging scheme is adaptive and can prioritise regions of interest.

A number of challenges remain, but potentially the technique can offer:

- Cheap, simple, efficient solution with (off-the-shelf components);
- Specific imaging;

- Low transmission rate;
- Programmable (machine vision techniques on board including compressive sensing);
- Works well in constellations;
- Multispectral (vis, mid-IR).

5 CEOI and UKSA plans for the next 3-5 years

5.1 UKSA Plans For EO

***Beth Greenaway**, UKSA*

Beth outlined current UKSA plans for EO in the window 2017 to 2040. UKSA immediate actions are to:

- Define and Lead EO strategy and policy development
- Enable growth of the EO and related sectors
- Position UK as a global leader in use of EO in applications and services
- Act as Sector sponsor for the EO community (nationally and internationally)

Achievements are many including:

- Implementation Plan
- CMIN16 - UK is the lead funder of EO activities in ESA – E285.8m
- Copernicus influence data and space elements
- French bilateral missions
- CEOS / GEO UK office and increased presence
- Climate Data Zone
- Space for Climate
- CEOI 2020
- Ground Segment Vision

Beth outlined a subtle change in philosophy aimed at exploiting our leading position in EO with ESA. The vision for the 2040 sees a greater coupling between EO missions, data use and applications, penetrating deeper into mass markets. On the way there are a number of potential game changers including:

- Data – high res / high frequency / video / commercial constellations
- Digital economy IT / cloud computing / big data analytics
- Brexit – industrial landscape
- Copernicus long term guaranteed operational data
- Space launch capability
- International policy

Some changes that will be visible include:

- Emphasis on International programmes
  - CEOS and GEO coordination office. Technical groups draw on and export UK strengths.
- Strategic approach to ESA
  - Using the ECSAT presence
  - Thinking about the long term (getting in early, proactive promotion of UK priorities)
  - Using domestic funding wisely - Technology Strategy.
- Skills and Education Plan – what do we need to do?

- Proactive dissemination of 'good news' to the non-specialist

5.2 CEOI Strategy Towards 2020 & Beyond

***Mick Johnson**, CEOI*

Mick summarized the new strategy for CEOI 2020. The objectives include:

- Guide investment of the UKSA EO technology funding
- Identify global EO opportunities and prepare UK technology teams for ESA, Eumetsat, Copernicus and export EO business
- Develop common understanding between CEOI, UKSA and ESA of UK technology capabilities and priorities
- Identify potential benefits from application of EO technologies into other applications (space and terrestrial) to maximise growth.

The existing strategy and the current methods of achieving the aims was outlined, as was the motivation to revisit the strategy for the new Phase. Mick summarized the outputs of the initial national capability analysis and the status of the current consultations with the community.

The delegates and the community were invited to send their thoughts on the new draft strategy, and were asked to consider the following questions:

- What is the role of technology demonstrators?
    - Do HAPS or airborne offer better opportunities than Cubesats?
- Should EO technology funding be segmented/pre-allocated?
    - By TRL, by markets or strategically; or is open competition best?
    - Can we join forces better with other funding sources?
- Should we continue to invest in technology for EO science missions?
    - Are Earth Explorers too uncertain?
    - Can we better exploit technologies developed for EO science for other opportunities?
- What are the highest potential commercial/export opportunities?
    - Are there specific technologies ripe for development?
- How can we fill the growing skills gaps for upstream technologies?
    - How can we map comprehensively UK capability and competition?
    - How should we respond?

6 International Perspective – Day 2

6.1 EO Technology Needs at ESA

***Massimiliano Pastena**, European Space Agency*

Max gave an overview of Earth observation Programmes, including meteorological & EUMETSAT programmes, Copernicus and the EU programmes, and the ESA Earth Explorers. He also reviewed ESA Technology developments for EO, and the ESA compendium of EO mission concepts.

The details are contained in the slides, but the proposed extension to the Copenicaus programme are of particular interest to the CEOI community. The missions include

- CO_2 Monitoring - Climate change

- Polar ice and ocean interferometry and altimetry - Climate change, marine and polar environment monitoring
- Other Polar (Arctic) observations - marine and polar environment monitoring
- Land thermal imaging - land monitoring, emergency management
- Soil moisture, ocean salinity - marine environment monitoring, land monitoring
- Hyperspectral land imaging - land monitoring, emergency management
- Next generation gravity mission.

For Earth Explorers, the EE9 call closed on 1st June and the EE10 call is expected around the end of 2017.

Max presented some technology activities related to UK interests, including the Swath Precipitation Radar Instrument, which has evolved into the WIVERN in-cloud wind mission concept.

Finally he showed the ESA EO mission compendium document which is available to interested parties. See the slides for details.

7 Innovative Microwave & Radar Developments

7.1 NovaSAR

***Martin Cohen**, Airbus Defence and Space*

Martin outlined the NovaSAR concept and the progress to date. The NovaSAR-S payload is an S-band Synthetic Aperture Radar developed with low cost in mind, while maintaining performance and offering attractive applications. The motivation is to facilitate commercial constellations of smallsat based SAR missions, thus leading to growth in the user base of SAR imagery. The realization of the concept involved the deep SAR knowledge of Airbus with the low-cost know-how of SSTL.

The resulting phased array concept was achievable owing to the development of GaN solid state power amplifiers, allowing 10x more power per phase centre, thus leading to 10x less phase centres needed on the antenna. The final payload design involves a master-class in tradeoffs and optimisations.

The instrument has 3 basic modes, one high-resolution (6m) stripmap mode, and 2 wide swath medium resolution ScanSAR modes. There is also an experimental maritime mode for ship detection.

NovaSAR is nearly complete, and launch is expected in Q3 2017.

7.2 Innovative SAR Technology

***David Hall,** Airbus Defence and Space*

David explored the drivers of innovation in SAR design. He described the Excelsior payload concept, which uses the GaN technology that enabled the NovSAR mission. Excelsior builds on NovaSAR, and is a more capable system, and provides X-band capability with potentially 1m resolution and with 1000Km swath in Maritime ship detection mode. The aim is to provide this capability with a similar price tag to NovaSAR-S.

The result will be a free standing payload that would be compatible with a range of satellite platforms. It could for example be accommodated on the PSLV launcher in dual launch configuration using the Astrobus-S platform.

Finally David summarized some mission analysis that examines how the orbit for an Excelsior mission could be configured for maximum spatial and temporal coverage.

7.3 94GHz Polarisation Diversity Doppler Radar To Observe Global In-Cloud Winds

Anthony Illingworth*, University of Reading and* ***Alessandro Battaglia****, University of Leicester*

WIVERN is a 94GHz scanning Doppler radar concept that will provide:

- in-cloud global winds to +/- 1 or 2 m/s;
- rain snow and cloud ice water content with 50km horizontal, and 1 km vertical resolution
- daily visits poleward of 50˚.

WIVERN uses a conical scan with a rotating antenna. The key parameters are:

- 800km wide ground swath
- Slant range of 651km
- Scan every 7 seconds, in which the spacecraft moves 50km along track, and samples every 50km along the arc.
- 2.9m elliptical antenna

The measurements will complement those of ADM Aeolus (Launch 2017), which only measures clear air winds, and scatterometers which only measure winds at the sea surface. Wind vector of this accuracy will be very useful in reducing weather forecast errors, as well as identifying developing storms before they hit land.

A key technique is polarization diversity, i.e. alternating H and V pulse transmissions, which allows high effective PRFs without introducing ambiguities due to pulse overlap. There is however some potential for depolarization, causing ghost echoes due to asymmetry in the wet hydrometeors, and due to the near surface echoes. This however appears to be manageable and detectable.

Anthony explored the detail of the radar techniques, the issues arising and the various deployment tradeoffs that need to be considered.

7.4 Instrumentation For 1-5 THz Heterodyne Sounders

Brian Ellison*, STFC RAL Space*

Brian explored the motivation for sounding the atmosphere in the THz region. He explained how THz sounding is enabled by the heterodyne technique, and he then explored the current status of the THz technology development.

Atomic oxygen, NO, OH and HO_2 all have prominent emission lines in the range 1- 5 THz. Hence THz spectra provide insight into atmospheric composition, which is related to climate change and weather. However as the atmosphere becomes increasingly opaque in the upper THz, mainly due to water vapour, ground based sensing is restricted to high and dry locations. Hence one turns to high altitude aircraft or spacecraft.

As the spectral resolution of THz instruments are arbitrarily fine, the resolution is limited by the local oscillator stability and the IF signal processing capability. By using a quantum cascade laser as the LO, specialized mixers and a digital spectrometer, a high performance THz instrument can be realized.

Brian summarized ground and lab based experiments with this technology, and introduced the LOCUS satellite payload concept, which is being developed with CEOI support. LOCUS features:

- Scanning LEO THz limb sounder targeting key upper atmosphere species
- Multi-THz Schottky diode heterodyne receivers.
- High spectral resolution, better than 3 MHz.
- QCL LO for band 1 and 2 (see Alex Valavanis talk).
- Compatible with small satellite platforms.

The mission targets the upper atmosphere in the mesosphere and lower thermosphere, which is influenced by both terrestrial and space weather.

7.5 Filterbank Spectrometers for Hyperspectral Microwave Atmospheric Sounding (HYMAS)

***Peter Hargrave**, University of Cardiff*

Peter described the development of superconducting filterbank spectrometers. These are realised as an array of high-Q superconducting micro-resonators coupled to a transition-edge superconducting detector . Each spatial 'pixel' is a broad-band antenna, coupled to up to ~1000 detectors, which results in up to 1000 spectral channels per spatial pixel. Such technology can cover <40GHz, up to ~1THz, and encompasses critical temperature and humidity sounding lines, as well as producing excellent sampling of ice particle size distribution. Devices can be fabricated using micro-fabrication techniques such as deep UV/e-beam lithography. The motivation is that all the benefits of the IR and MW sounders can be combined into a single instrument, covering all channels of the 3 MetOp-SG instruments with greater sensitivity and resolution (spatial and spectral).

These are cryo-devices and must be cooled to sub-Kelvin temperatures to work. Suitable space-qualified cryocoolers are available from the astronomy domain (Planck, Herschel, JWST). The remaining issue is one of radiator design (for dissipating waste heat from the cryocooler) for operation in LEO, and a study (unfunded) has been initiated to look at this.

7.6 Microwave Radiometry For Accurate Coastal Altimetry

***Janet Charlton,** JRC Systems*

Radar altimeter measurements over ocean are subject to path delay errors due to the wet atmosphere. This is normally addressed by a passive microwave radiometer (MWR) with footprint co-aligned with the altimeter footprint. This provides the wet tropospheric correction. Traditional MWR systems have a wide footprint, and while operating over open ocean, this is perfectly acceptable. However over coastal regions and inland water the measurements are compromised by land brightness temperature contamination in the MWR footprint.

JCR Systems is leading a third ESA study in advanced microwave radiometers designed to improve the wet tropospheric correction over coastal and inland water regions in particular, in order to capitalize more fully on the capabilities of the latest generation of altimeters. Missions targeted include next generation Sentinel 3 and JASON-CS plus.

A next generation MWR for altimetry therefore must feature:

- The 'classical' MWR channels to ensure measurement continuity;
- High frequency channels for enabling accurate altimetry in coastal and inland water regions.

This leads to the following design goals:

- Improved spatial resolution
- Improved spatial discrimination
- Improved radiometric accuracy for non sun synchronous missions.

Janet considered a number of mission options as well as possible system designs, calibration systems and technology choices. She noted that although the target missions are operational in nature, they are still driving new technology requirements.

8 Detectors

8.1 Quantum Cascade Lasers For Heterodyne Techniques

Alex Valavanis, *University Of Leeds*

Alex considered the LOCUS mission requirements in the range 1-5 THz, and the technologies required to satisfy these requirements, including THz quantum cascade lasers (QCL), and waveguide-integrated THz QCL systems.

The local QCL oscillators used by LOCUS are tiny devices of low mass, delivering ~ 1mW of laser power. Input power is also modest at less than 5W. The devices are tunable over a 4GHz range, and are fully integrated with a space-qualified cryo-cooler.

QCLs address a gap in the THz domain, which is difficult to address with other technologies, at least not at these mass and power levels.

Alex addressed options for LO QCL integration, and described the LOCUS solution, using a 3.5 THz QCL integrated into a precision micro-machined copper waveguide block containing an integrated temperature sensor. A dual feedhorn mixer block was shown, providing access to both facets of the QCL enabling simultaneous coupling with both the mixer and stabilization subsystem.

Successful waveguide integration of QCLs has been demonstrated, and the next steps are:

- Complete system breadboarding
- Stabilisation subsystem integration
- Mixer integration
- Airborne/in-orbit demonstration

8.2 Detectors For Mm Wave & Thz

Peter Huggard, *STFC RAL Space*

Peter described a range of devices operating in the THz region, which may/will have applications in Earth observation. These included:

- Rectifying THz video/power detectors
- InGaAs detector diodes
- Quasi-optical detectors - featuring sinuous micro antennas with integrated diode chip mated with a 10mm diameter lens.
- Waveguide devices – with example of a W-band device
- MetOp low noise amplifiers – with discussion of requirements and performance

Possible applications include:

- Lab spectroscopy
- Imaging
- Diagnostics on particle accelerators
- Remote sensing radiometers, when used with low noise amplifiers

8.3 Latest Developments At Leonardo In IR Detection For Earth Observation

***Peter Knowles**, Leonardo*

Peter summarized recent Leonardo work on IR detectors which is of interest to the EO community. This includes for ESA:

- SWIR 2k x 2k detectors
- Visible region hybrid CMOS devices in collaboration with Teledyne e2v
- Proton and gamma testing of MCT APDs

With CEOI and NSTP support:

- Extending the SWIR spectral response
- Proton testing of LFNIR devices
- Alternative TGS pyro-electric crystal growth.
- 4 megapixel APD array

Target missions include:

- IASI NG on MetOp SG
- DLATGS on OSIRIS-REx
- HOPE Mars Orbiter
- FORUM (EE-9 candidate)

Peter described more detailed aspects of device functionality, including techniques of radiation hardening and multilayer coatings for improved performance.

8.4 Technology Developments In Earth Observation Imaging

***Joe Gannicliffe**, Teledyne E2v*

Joe surveyed the current status of the company's EO sensor types, operating modes and current missions. He then went on to explore future developments in CMOS, and TDI CMOS. He then examined challenges, options for low cost imaging systems, and some solutions to the challenges.

Current sensor types include those analogous to digital camera 2D sensors, which work well in geostationary deployments, but are less useful in LEO with relatively high ground speed. For this application, linear push-broom detectors are used, which can be used in monochrome or multispectral applications (with multi-line linear sensors). Push broom concepts are easy to to transition to CMOS. An extension of the linear detector is the Time Delay and Integration (TDI) CCD technique which uses multiple rows of pixels, which can be clocked in sync with the image motion, accumulating photons in the process to improve signal to noise ratio.

Joe then gave some examples of sensors and the EO imagery that can be obtained.

Future mission requirements include wider 17wath width, and higher ground resolution, which leads to longer sensors with more columns and smaller pixels, which again leads to the need for very fast readout rates. These requirements drive one towards CMOS. A charge clocking process similar to CCD TDI can be used, and data can be digitized and read out with low noise and high line rate.

Integrated focal plane assemblies (FPAs) can satisfy requirements for low-cost miniature instruments e.g. for cubesats, and filters can be directly fabricated onto devices, making essentially a plug and play FPA.

8.5 Low And High Voltage Asics For Space Imaging

***Nick Waltham**, STFC RAL Space*

Nick summarized the requirements for CCD camera readout electronics, and how these can be satisfied using specialized ASIC devices. A number of points were raised:

- Logic is usually implemented in a radiation tolerant FPGA;
- Clock waveforms must be converted from standard logic levels to ~10V amplitude analogue signals having sufficient current to drive the CCDs capacitive circuitry.
- Charge detection amplifiers several low noise DC bias voltages, typically 30V for Output Drain Bias and 17V for Reset Drain Bias
- Video output signal swing is ~1V

Overall space system requirements require low mass and low power devices, at low volumes. Devices must be high reliability space components, and must be radiation tolerant. Such devices may difficult to source, or completely unavailable. Up-screened commercial components may not meet project requirements.

The approach at RAL Space is therefore to design and build space qualified low and high voltage mixed signal ASICs.

Nick described some current ASIC designs and the associated space missions in which they have been used. He described the technology roadmap and areas where work is continuing. The Low-Voltage CCD ASICs have been successfully demonstrated, but susceptibility to single event latchup (SEL) remains. Hence future work will concentrate on:

- Radiation hardening against SEL
- Greater functional integration
- High voltage CCD ASICs
- Multi-die hybrid packaging technologies
- Responding to requirements from large focal plane arrays of tiled CCDs with multiple video output ports.

9 Future Trends

9.1 Plans For AIT & Calibration At RAL's R100 Building

***Chris Mutlow**, STFC RAL Space*

Chris summarized plans for the next phase of development of the National Satellite Test Facility (NSTF) within RAL Space's R100 facility. The need for a comprehensive UK spacecraft environmental test facility has been identified through the UKSA's Facilities and Gaps Study carried out as part of the IGS via surveys and workshops with UK industry over the last 18 months. The facility will support competitiveness and strategic capability of the UK space community, and will be particularly important post-Brexit. It will provide complete environmental test capability for a large spacecraft at a single location. Facilities include:

- Clean rooms for satellite build and preparation;
- Vibration & pyrotechnic shock testing;
- Centre of Gravity and Moment of Inertia;
- Acoustic testing
- Thermal vacuum testing
- ElectroMagnetic Compatibility and Compact Antenna Test Range

NSTF aims to provide UK industry with a "one stop shop" for complete environmental testing of complex spacecraft and space systems. The specific facility needs and requirements were established through dialogue with specific input from Airbus D&S, TAS UK, SSTL and LM UK plus their associated supply chains. UK MoD needs are also addressed. Key capabilities will be:

- Full EVT for satellite size up to 7 tonnes (wet)/ envelope
- 3.5m x 3.5m x 7m (transportation container)
- Secure and Tempest compatible
- ISO9001 and ESA Certified (possibly UKAS)
- Available by late 2019 /early 2020
- Able to process at least 3 spacecraft EVT campaigns per year

NSTF will operate (at least initially) on the same proven basis as existing STFC RAL Space facilities:

- Basic facilities operated and supported by RAL Space
- Programme specific staff and resources provided by industrial user
- First come/ first served with committed facility slots; inevitable programme slips accommodated on a negotiated basis
- Services charged at full economic return rates
- Evolution of operating models may be evaluated in conjunction with industry, STFC and other stakeholders once NSTF is fully established

9.2 Optical Metamaterials & Novel Techniques

***Robert Lamb**, Leonardo*

Robert spoke about novel optical techniques being considered and explored at Leonardo. These include planar ultra-thin lenses that exploit antenna-like sub-wavelength structures (meta-materials), using the lithography techniques from the semiconductor industry. The aim is to demonstrate lightweight lenses suitable for imaging and beam focusing for the visible and IR bands. Practical microscope objective lenses have been realized and Leonardo are considering whether the concept can be upscaled to larger lenses. A second area of investigation was the use of 2D mosaic filters for single frame multispectral imaging. Work is underway in collaboration with University of Oxford to develop matrix completion methods to derive high-resolution images from incomplete data cubes, which have been under sampled using mosaic filters. The work has application in the multispectral imaging of moving objects where system latency reduces the time allowed for data acquisition.

9.3 Simulation Study For Ku-Band Microwave Radiometry Of The Polar Atmosphere

David Newnham*, British Antarctic Survey*

David explored a new technique that BAS are using for sounding of the polar atmosphere using Ku-band microwave radiometry. Space weather affects the polar middle atmosphere. There are ~1250 magnetospheric substorms annually, resulting in high energetic electron flux. This results in hydroxyl ions at 70-80 km and also affects mesospheric ozone. Measurements of O_3 and OH are needed to verify model predictions.

The sounding technique uses satellite ~TV signals in a bistatic mode. Radiometers are assembled from COTS TV components (which operate in the Ku band (10.7 – 13.25 GHz). David gave details of the retrieval scheme, and how the interference from background species is dealt with. Davi concluded that:

- Simulation techniques have been developed for modeling the retrieval of ozone and OH vertical profiles from 11–14 GHz microwave observations.
- Ku-band observations are highly applicable to future microwave instruments designed to study space weather events, atmospheric dynamics, planetary scale circulation, and chemical transport for polar and global climate modeling.
- Ground-based passive microwave remote sensing complements space-based EO.

9.4 Innovative Materials for EO Missions & Beyond

Alex Brinkmeyer*, Oxford Space Systems*

Oxford Space Systems is a VC backed company specializing in next-generation deployable structures. The aim is to use flight-qualified proprietary materials and folding techniques inspired by origami to produce lighter, less complex, more stowage efficient, and lower cost systems than exist at present. OSS sees deployable structures as an enabler of EO technology with the aim to drive down cost and increase accessibility to space. Products include:

- Large deployable antennas;
- AstroHinge deployable panel arrays;
- AstroTube scalable boom systems.

Antenna products in development include:

- Microsat RF patch arrays;
- Umbrella-like wrapped-rib antennas which can be stowed in a 6U microsat, and are suitable for frequencies up to Ka-band;
- Large unfurlable antennas scalable to 4m – 12m;
- Log-periodic antennas – using tape springs – to 6m in length

CEOI is funding development of a large Cassegrain deployable antenna to TRL 3 to validate materials, surface treatments to endure the space environment

9.5 Cold Atom Techniques In Gravity Mapping

Tristan Valenzuela, *STFC RAL Space*

Tristan gave a brief overview of the potential uses of quantum technologies in space. These include:

- **Earth Observation** – cold atom interferometry can allow high sensitivity gravity measurements in support of geodesy, ocean circulation, glacial movements and earthquake monitoring.
- **Fundamental physics** – via atomic clocks and atom interferometers that can be used for tests of the equivalence principle, gravitational red shifts and gravity wave detection.
- **Telecommunication and navigation** – via atomic clocks and optical links, enabling global time references, high accuracy navigation, internet synchronization, deep space ranging and communications, increased spectral efficiency and data rates, and secure communication via quantum key distribution (QKD).

The talk focused on gravity measurement, and the basic measurement techniques available were reviewed. To go beyond CHAMP, GRACE and GOCE, new techniques are required to achieve the desired sensitivity. The promise is that we can go from 100km resolution as with GOCE to ~10km with quantum techniques.

Tristan explained how the atom interferometer works and how it can be used to measure gravity. He reviewed the various programmes around the world. He showed the lab bench level complexity, and discussed progress in configuring this for possible spaceflight.

RAL Space they are concentrating on:

- Development of Ancillary Technologies
  - Partnering in Innovate UK projects for the development of:
    - Space qualified lasers (in the visible domain)
    - Space qualified laser control electronics

- Leading an ESA TRP activity
  - Design and characterize a vacuum chamber able to deliver an ultracold atomic clouds at a 1Hz rate

- Development of Own Capabilities
  - Full experiment control electronics (to be space qualified)
  - Cold Atoms test bed facility and optimization studies