

Optical Frequency Combs for Optical Space Instrument Calibration and Terahertz Generation for Heterodyne Detection.

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ABSTRACT

Optical frequency combs (OFCs) offer a compact and versatile photonic technology that can address several challenges associated with future space based scientific instrumentation. This work presents the results of the European Space Agency MiCoSMic project, which investigated the application of integrated OFCs for two applications: Optical Space Instrument Calibration (OSIC) and Terahertz Generation for Space Heterodyne Instrumentation (THZG). Two breadboard demonstrators were developed: a Microcomb Module based on Kerr soliton generation in a silicon nitride micro-ring resonator, and a Terahertz Module based on an injection-locked gain-switched optical frequency comb architecture. For the OSIC application, validation testing demonstrated a broadband Kerr soliton comb spanning 1350-2005 nm. All measurable comb tones exceeded the required optical power threshold of 0.1 μ W, while the measured comb spacing of 384.5 GHz satisfied detector sampling constraints. For the THZG application, photomixing of Kerr comb tones generated a THz carrier at 769.041 GHz, meeting the frequency accuracy requirement of <100 MHz and demonstrating linewidth and stability performance consistent with the application requirement of <1 MHz. A hybrid architecture combining Kerr and injection-locked gain-switched combs was also demonstrated, enabling access to a wider range of THz carrier frequencies.

1. INTRODUCTION

Optical frequency combs (OFCs) have become an increasingly important tool for many scientific instrumentation applications as they link the optical and microwave domains [1]. They have been utilized across a number of application areas such as dual comb spectroscopy [2], and coherent telecommunications [3]. The work presented in this paper results from the MiCoSMic project, which focused on the development of OFC sources for use in two space based applications: Optical Space Instrument Calibration and Terahertz Generation for Space Heterodyne Instrumentation. The project explored the integration of two types of OFCs, dissipative Kerr soliton combs [4] and gain-switched combs [5], which offer complementary features. Kerr soliton combs are generated through the simultaneous balance of Kerr nonlinearity and dispersion, as well as between parametric gain and cavity loss, when a high quality-factor (Q-factor) dielectric microcavity, such as a micro-ring resonator, is optically pumped, typically with a high-power, continuous-wave optical source. Broad spectral coverage is achievable with this comb architecture. However, the separation between comb lines, or free spectral range (FSR), is set by the geometry of the micro-ring resonator. Gain-switched optical frequency combs are generated through the direct modulation of the DC bias of a semiconductor laser around its threshold current. Gain-switched combs have complementary trade-offs to Kerr soliton combs, particularly in terms of spectral bandwidth and tunability. In general, gain-switched OFCs provide more limited spectral coverage than Kerr soliton combs, typically spanning only a few nanometres. However, gain-switched optical frequency combs offer a comparatively simple generation architecture, and a high flexibility, electronically tunable FSR. The integration of these two comb types can be used to overcome the limitations of each. Within this work two breadboard demonstrators were design and manufactured, each based around one of the comb technologies. Two validation test campaigns were conducted using these breadboard demonstrators to assess the suitability of the comb technology in the chosen application areas.

2. BREADBOARD DEMONSTRATOR CONCEPT AND DESIGN

Within the project, two demonstrator modules were designed and developed to validate optical frequency comb technology against application driven requirements derived from the representative future space missions. Two application areas were selected for investigation due to the potential benefits offered by optical frequency comb technology: Optical Space Instrument Calibration (OSIC) and Terahertz Generation for Space Heterodyne Instrumentation (THZG).

Table 1. OSIC application requirements derived from the VenSpec-H instrument.

Parameter		Requirement
Spectral Coverage	VenSpec-H Band 1	1165 – 1180 nm
	VenSpec-H Band 3	1720 – 1750 nm
	VenSpec-H Band 4	1370 – 1390 nm
Minimum Comb Line Spacing		≥ 0.23 nm
Wavelength Stability		≤ 0.005 nm
Optical Power per Comb Tone		≥ 0.1 μ W

Table 1 summarises the key application level requirements that would be targeted for the Optical Space Instrument Calibration (OSIC) application. These were derived from the calibration needs of the VenSpec-H instrument, one of the scientific payloads proposed for the European Space Agency’s EnVision mission. The spectral coverage requirements were obtained from the VenSpec-H wavelength bands of interest, while the minimum comb line spacing requirement was derived from the detector sampling characteristics to avoid spectral oversampling. Requirements on wavelength stability and optical power per tone were defined to ensure that the generated comb could provide a stable and detectable calibration reference across the operational spectral range.

Table 2. THZG application requirements derived from the Keystone Mission Concept (formerly LOCUS).

Parameter	Requirement
Frequency	< 800 GHz
Linewidth	< 1 MHz
Frequency Stability	< 1 MHz
Accuracy	< 100 MHz

Table 2 summarises the key application level requirements that would be targeted for the Terahertz Generation for Space Heterodyne Instrumentation (THZG) application, derived from the needs of the local oscillator (LO) sources for the Keystone mission concept (formerly LOCUS). For the present activity, the targeted carrier frequency was < 800 GHz. To ensure suitability as a local oscillator source, spectral purity requirements of a linewidth below 1 MHz, frequency stability better than 1 MHz over a timescale of seconds, and a frequency accuracy better than 100 MHz were required.

OFCs offer a compact and highly stable source of equally spaced spectral lines, making them attractive for both calibration and frequency generation applications. For OSIC, the generated comb spectrum provides a dense set of wavelength references spanning multiple spectral bands. For THZG, the comb lines from OFCs can be used for the generation of THz carriers through optical heterodyning. To validate these concepts, two demonstrator modules were implemented as laboratory breadboards in a 19-inch rack mounted form factor, with the primary objective of validating the OFC technologies and assessing their suitability for the targeted applications. Consequently, the activity focused on proving technical feasibility and performance, rather than addressing environmental robustness, miniaturisation, or flight qualification aspects required for space deployment.

The first demonstrator, hereafter referred to as the Microcomb Module, was designed to generate a Kerr soliton comb. The output from this module would be validated directly against the OSIC application requirements. This module would also provide a set of stable optical tones for use within the THZG hybrid comb architecture. A simplified block diagram of the Microcomb Module is shown on the lefthand side of Figure 1. The Microcomb Module consisted of a narrow linewidth continuous wave pump laser, a high-power erbium-doped fibre amplifier (EDFA), a polarisation controller, and a packaged silicon nitride micro-ring resonator. Polarisation control was implemented to maximise coupling into the desired resonator mode and enable reliable access to the soliton operating regime. Control electronics provided pump wavelength tuning and

resonator thermal control, while a photodetector was used to monitor the resonator transmission response during soliton initiation.

The second demonstrator, hereafter referred to as the Terahertz Module, was designed to generate a gain-switched optical frequency comb. For the THZG application, the Kerr soliton comb generated by the Microcomb Module was provided as an optical input to the Terahertz Module, where selected comb tones were utilised within a hybrid optical frequency comb architecture. This architecture leveraged the large free spectral range of the Kerr soliton comb to enable access to high-frequency comb line separations, while the gain-switched comb provided flexibility in selecting the target THz carrier frequency. A simplified block diagram of the Terahertz Module is shown on the left-hand side of Figure 1. The Terahertz Module consisted of a high-speed distributed feedback (DFB) laser, an RF amplification chain driven by an external RF synthesiser, an optical filter, and multiple EDFAs. A selected Kerr comb tone was used to injection-lock the DFB laser. Subsequent gain-switching of the injection-locked laser generated a comb that inherited the coherence and frequency stability of the Kerr soliton comb. In parallel, optical filtering and amplification stages were used to isolate a second Kerr comb tone. This tone was subsequently combined with the gain-switched comb to realise the hybrid architecture used for THz carrier generation through optical heterodyning. The optical signal was coupled to a waveguide-integrated photodiode antenna (WIN-PD), where photomixing occurred [6]. The generated THz signal was subsequently emitted into free space.

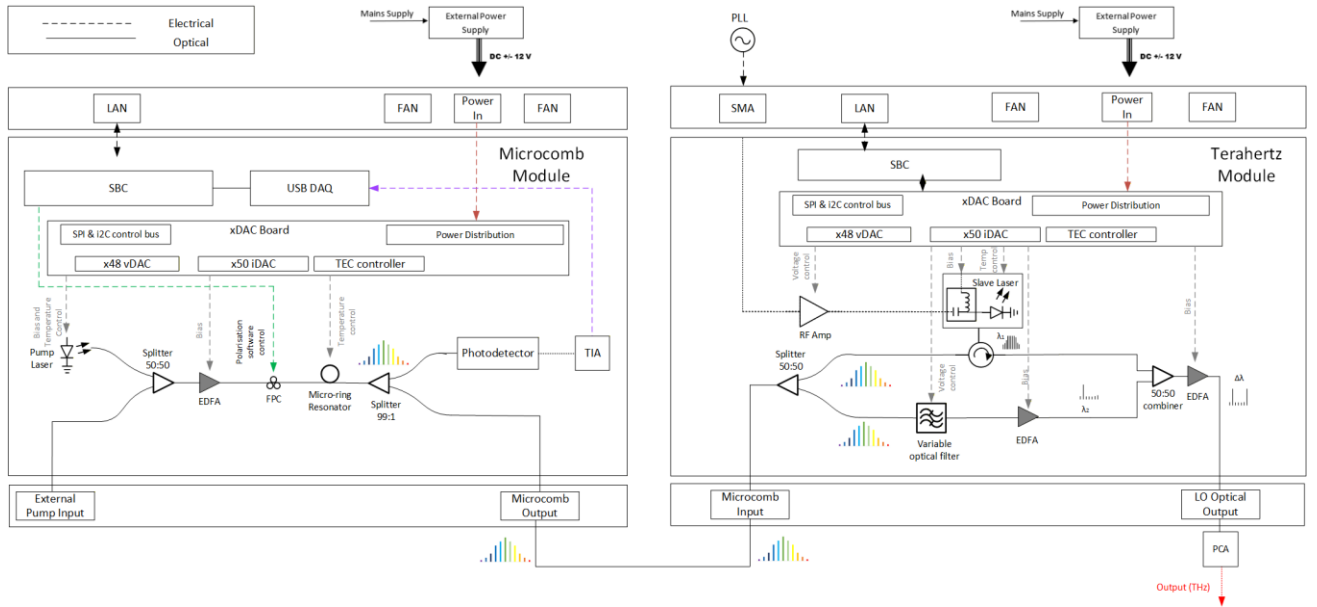


Figure 1. Block diagram of the Microcomb and Terahertz Modules.

3. FUNCTIONAL VERIFICATION OF THE BREADBOARD DEMONSTRATORS

The core component within the Microcomb Module was the packaged micro-ring resonator (MRR) sample. The MRR was packaged in a standard gold box 14-pin butterfly package, in a fiber-in/fiber-out configuration. The package included a thermoelectric cooler (TEC) and thermistor to allow for set point temperature control. The MRR, which was secured on top of a subcarrier for stability, sat on top of the TEC within the package. The thermistor was placed in a location close to the chip for accurate temperature measurements. Lens ended fibers were used for coupling light into and out of the facets of the micro-ring resonator.

One of the key challenges associated with soliton generation is the thermo-optic instability that arises in the microresonator when the pump wavelength is tuned to the red side of the cavity resonance. While a number of techniques have been developed to overcome this instability, including power-kicking [7] and fast scanning [8], this work used a dual-mode pumping scheme to mitigate this issue [9]. To identify a suitable dual-mode resonance for pumping, the transmission spectra TM polarisation of the micro-ring resonator was measured. This was measured using a swept laser source operating at -3 dBm to minimize thermal perturbations. TM polarization was selected using a fibre polarization controller positioned before the packaged MRR. The package was maintained at 20°C during measurement. The output power from the packaged MRR was recorded using a power meter while the wavelength of a swept laser was scanned from 1560 to 1570 nm. Synchronisation of the laser sweep and power measurements enabled accurate acquisition of the transmission spectrum. The resulting transmission spectrum, shown in Figure 2, was used to identify the resonances of the MRR and determine their corresponding Q-factors. The fundamental mode, TM_{00} , was located at 1565.817 nm and had a loaded Q-factor of 6.9×10^5 , while the auxiliary mode, TM_{01} , was located at 1565.866 nm and had a loaded Q-factor of 1.7×10^5 . The separation between the dual modes was 49 pm, which is suitable for dual mode pumping.

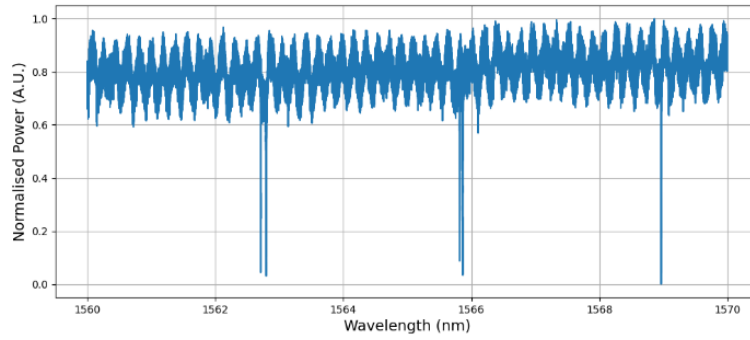


Figure 2. Transmission spectrum measured at low input power before MRR package was integrated into Microcomb Module.

Following the transmission measurements, the packaged MRR was incorporated into the Microcomb Module, where Kerr soliton generation was subsequently demonstrated. A low-linewidth DFB laser was used as the optical source for pumping the MRR, with drive current maintained at 200 mA and wavelength tuning achieved through temperature control. The output from the pump laser was amplified to 29.5 dBm, the power level required for soliton generation, using a high-power EDFA. The pump light was then passed through a motorised polarisation controller to optimise the polarisation of light input into the MRR. A 99:1 splitter was connected to the output of the MRR package, with 1% of the optical power directed to a photodetector for monitoring the resonator transmission during comb generation, while the remaining 99% formed the Microcomb Module output.

The input polarisation was adjusted until the characteristic soliton step was observed in the transmission spectrum. This feature, highlighted by the red box in Figure 3, appears as the region between a sharp decrease and subsequent increase in transmitted power. The soliton step corresponds to the detuning range over which dissipative Kerr solitons can exist within the resonator and is therefore an important indicator for soliton generation. Once the soliton step has been identified, the polarisation state was fixed and the pump wavelength was tuned from shorter to longer wavelengths by varying the temperature of the pump laser. As the pump wavelength was detuned into the soliton step region, stable Kerr soliton generation could be achieved.



Figure 3. High power transmission spectrum, with the soliton step highlighted with the red box.

The optical spectrum of the generated comb was measured using an optical spectrum analyser (OSA) with an upper wavelength limit of 1750 nm. Consequently, the optical spectrum shown in Figure 4 does not capture the full extent of the comb, which is expected to extend to beyond 2000 nm. The resulting soliton microcomb generated by the module was subsequently used for validation testing in Application 1: Optical Space Instrument Calibration.

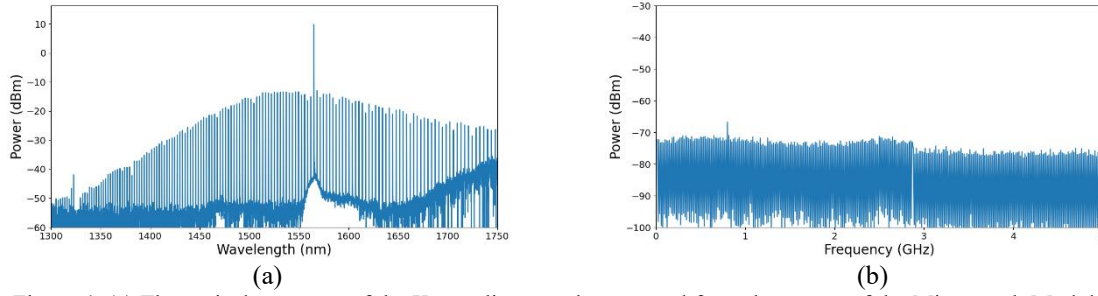


Figure 4. (a) The optical spectrum of the Kerr soliton comb measured from the output of the Microcomb Module and (b) the electrical spectrum of the low frequency noise.

To validate the integration of the two demonstrator modules, the Kerr soliton comb was generated from the Microcomb Module and directed to a 90:10 optical splitter. 10% of the optical power was sent to an OSA for continuous monitoring of the comb spectrum during testing, while the remaining 90% was routed to the Terahertz Module, which contained the components required for gain-switched comb integration. Within the Terahertz Module, a 50:50 splitter divided the incoming comb equally between two optical paths.

Path 1 contained a high-speed DFB laser, subsequently used to generate the gain-switched comb. The synchronisation between the two comb sources was enabled using optical injection. Optical injection is the process of using light from one source to coherently drive, control, or lock the behaviour of another optical device. This allowed for phase synchronization between the two comb sources. Figure 5 shows the optical spectra of the DFB laser before and after injection locking to a comb line from the Kerr soliton comb. All optical spectrums were measured with a 15 dB attenuator on the input to the OSA. In Figure 5 (a), the wavelength of the DFB laser is observed to be positioned higher in wavelength compared to the Kerr soliton comb line. The zoomed in optical spectrum of the DFB laser, shown in Figure 5 (b), shows a broad linewidth. When the wavelength of the DFB was decreased so that it aligned with the neighbouring Kerr soliton comb line, as shown in Figure 5 (c), optical injection locking was observed. The zoomed in optical spectrum after injection locking, shown in Figure 5 (d), shows a vast improvement in the noise profile of the DFB. The linewidth of its output has reduced to align with the linewidth of the Kerr soliton comb, showing that the DFB is now locked to the Kerr soliton comb.

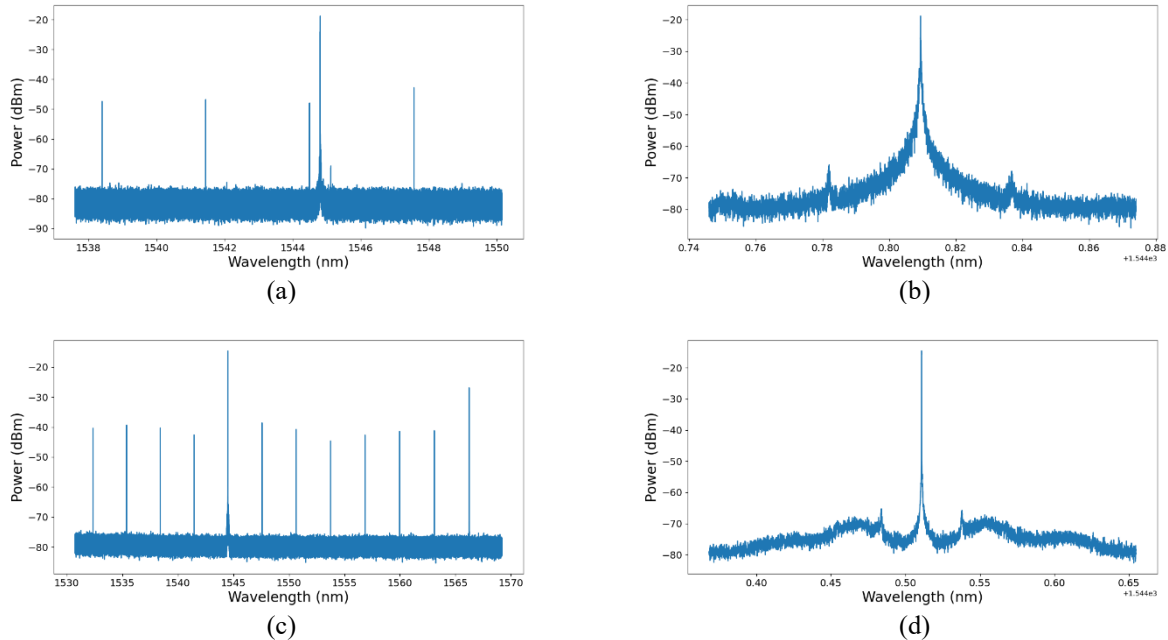


Figure 5. Optical spectra showing (a) the DFB laser in an unlocked state with the Kerr comb line at a lower wavelength, (b) a zoomed in spectrum of the unlocked DFB, (c) the DFB aligned with the Kerr comb line and (d) a zoomed in spectrum showing the noise improvement in the DFB, showing injection locking has taken place.

Path 2 was used for filtering and amplifying a single comb line from the Kerr soliton comb. The second optical path focused on the filtering and amplification of a single Kerr comb line. The filter was set to a central wavelength of 1547 nm with a bandwidth of 0.2 nm. This allowed for the filtering of a comb line which was adjacent to the one which was used for injection locking the DFB. This was chosen due to the available bandwidth of the measurement equipment. However, if a

higher frequency is desired, the central bandwidth of the filter can be varied to pick out any of the Kerr soliton comb lines within the C-band. The filtered comb was then amplified to 6 dBm using an EDFA.

The output from both paths were recombined using a 50:50 recombiner. The recombined optical spectrum is shown in Figure 9 (a). This is before the RF gain-switching signal was applied to the DFB. Figure 6 (b) shows the recombined optical spectrum once the gain-switching frequency has been applied to the DFB. As the Kerr comb was injected into the DFB, weaker modulation sidebands are observed on the other comb lines. The gain-switching signal used was at 12.5 GHz, with an RF power of 24.9 dBm applied to the DFB. The resulting injection-locked gain-switched comb is observed, and the functionality of the demonstration modules validated.

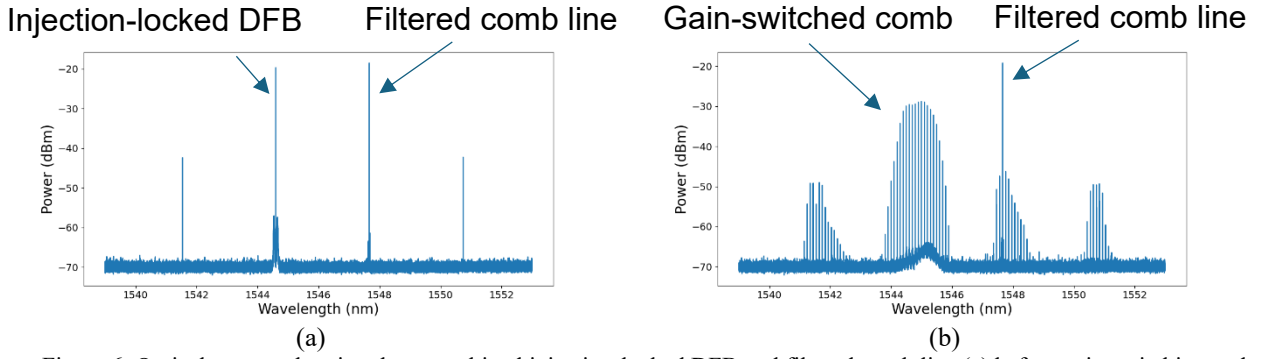


Figure 6. Optical spectra showing the recombined injection-locked DFB and filtered comb line (a) before gain-switching and (b) after gain-switching.

4. APPLICATION 1: OPTICAL SPACE INSTRUMENT CALIBRATION

High resolution spectrometers are widely used in planetary science missions to measure the spectral signatures of atmospheric constituents. The accuracy of these measurements depends on the ability to associate each detector pixel with a precisely known wavelength, requiring accurate and stable wavelength calibration throughout the mission lifetime. Traditional calibration sources can be limited in terms of spectral coverage, stability, size and power consumption. Optical frequency combs, such as the Kerr soliton comb, provide an attractive alternative due to their ability to generate a stable set of equally spaced spectral lines across a broad wavelength range. As such, validation testing aimed to assess the performance of the output from the Microcomb Module against the application requirements derived from the VenSpec-H instrument. Testing focused on verifying compliance with key application requirements, including spectral coverage, comb spacing, wavelength stability and optical power per comb tone. All measurements were performed at atmospheric pressure and room temperature under ISO-5 environment.

The validation test campaign was carried out using a Bentham DTMc300 double-monochromator with a focal length of 30 cm and a lead sulfide (PbS) detector using phase sensitive detection. A mechanical chopper positioned at the entrance slit was used to modulate the incoming optical signal and improve measurement sensitivity. The spectrometer was configured using the diffraction grating covering the spectral range between 1100 and 2200 nm, which encompassed the wavelength bands of interest for the OSIC application. The reported wavelength accuracy of the measurement equipment was in the order of ± 0.25 nm. The output from the Microcomb Module was coupled into the spectrometer using an optical collimator aligned to the entrance slit. The validation campaign consisted of 24 comb measurements acquired over a 14 day period, with daily calibration measurements performed to monitor the stability of the spectrometer wavelength scale.

A low-pressure mercury-neon (Hg-Ne) spectral lamp was integrated into the test setup to provide a stable wavelength reference throughout the campaign. The eleven atomic lines of the Hg-Ne spectral lamp selected for the monitoring of the wavelength scale are shown in Figure 7 (a). During pre-campaign characterisation, the strongest available Hg line (1529.28 nm) was scanned 20 times. The observed 1σ dispersion of the peak line position was ~ 0.004 nm, demonstrating sufficient precision for stability measurements. During the test campaign, all eleven lines were measured and compared against their known reference wavelengths before measurements of the OFC took place, enabling tracking and correction of any wavelength drift during post processing. Prior to the optical frequency comb measurements, three scans were performed with the Hg-Ne spectral lamp placed close to the optical chopper in front of the entrance slit of the double-monochromator to improve the signal-to-noise ratio of the measurement.

Figure 7 shows the wavelength drift of the spectrometer relative to the initial measurement, determined from repeated measurements of 11 Hg-Ne atomic emission lines acquired throughout the validation campaign. The observed drift ranged between approximately $+0.04$ nm and -0.09 nm over the monitoring period. These reference measurements were used to track and compensate for long-term drift in the spectrometer wavelength scale, resulting in an effective residual uncertainty of approximately 0.02 nm for subsequent comb measurements.

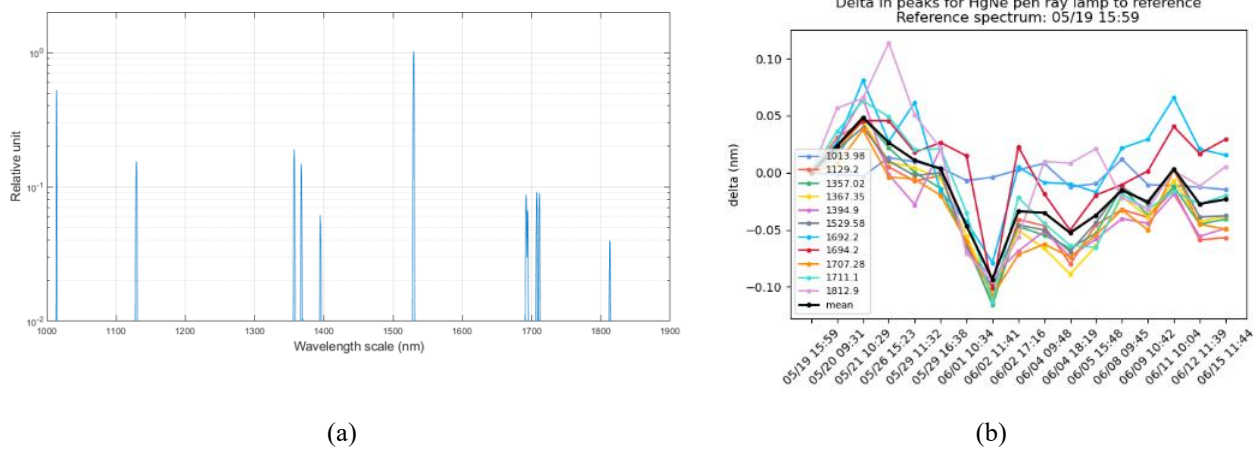


Figure 7. (a) Spectral lines of the Hg-Ne spectral lamp selected for the monitoring of the wavelength scale and (b) the results from daily monitoring of the Bentham DTMc300 wavelength scale over the course of the validation test campaign using the selected atomic lines for a shift normalized to the first measurement.

To enable assessment of the optical power per comb tone, the double-monochromator was radiometrically calibrated during the campaign using a NIST-traceable secondary standard of spectral irradiance, consisting of a 1000 W FEL-type quartz tungsten halogen (QTH) lamp. The lamp (FEL #546) was positioned 50 cm from the entrance slit and operated at a DC current of 8.2 A in accordance with the calibration conditions specified in the lamp certificate. The resulting system response function, measured over the wavelength range from 1100 to 2200 nm, is shown in Figure 8. Atmospheric water vapor absorption features located near 1.34 μm and 1.85 μm were not corrected in this first-order calibration and are therefore visible in the response curve. The detector output is reported in units of VDC, corresponding to the rectified and integrated voltage produced by the phase sensitive detection electronics. This response function was subsequently used to convert the measured comb spectra into absolute power values, enabling verification of the optical power per tone requirement.

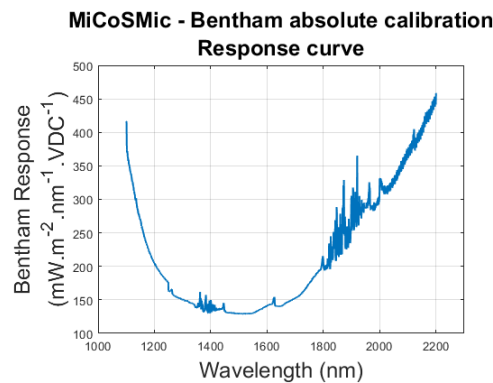


Figure 8. Response curve of the Bentham DTM300 double spectrometer obtained with the NIST F546 calibrated QTH 1000 W lamp.

To evaluate both the spectral coverage and optical power per comb tone of the Kerr soliton comb, the calibrated spectrometer response was combined with an assessment of the effective collection area of the detection system. Although the entrance slit height was 22 mm, the active detection area was limited by the dimensions of the PbS detector (3 mm $\times$ 3 mm) positioned immediately behind the exit slit. Experimental characterisation showed that only the central portion of the entrance slit contributed significantly to the detected signal. By progressively masking the slit height during measurements with the calibrated FEL lamp source, the effective active area was estimated to be approximately 3 mm $\times$ 0.5 mm, corresponding to a collection area of 1.5 mm².

The comb spectrum was measured over the wavelength range 1100-2200 nm using a wavelength sampling interval of 0.2 nm. This was repeated 24 times over the course of the validation campaign. Following radiometric calibration, the measured signal was converted to spectral irradiance and subsequently to spectral power at the slit entrance. The resulting spectrum is shown in Figure 9. Based on the calibrated response, the detection limit of the measurement system was estimated to be approximately $5 \times 10^{-3} \mu\text{W}/\text{nm}$. Comb tones were detected over the wavelength range from 1350 nm to 2005 nm, corresponding to a spectral bandwidth of approximately 655 nm. No comb lines were observed outside this interval. Since the spectrometer response had been independently verified between 1100-1350 nm and 2005-2200 nm using the calibrated FEL source with adequate signal-to-noise ratio, the absence of detectable comb tones in these regions was attributed to the spectral emission characteristics of the comb itself rather than limitations of the measurement system. The measured

spectral coverage encompasses the VenSpec-H Band 3 (1720-1750 nm) and Band 4 (1370-1390 nm) requirements derived for the OSIC application. However, the spectral bandwidth of the comb did not encompass VenSpec-H Band 1 (1165-1180 nm). This was observed across the 24 comb spectrum measurements acquired.

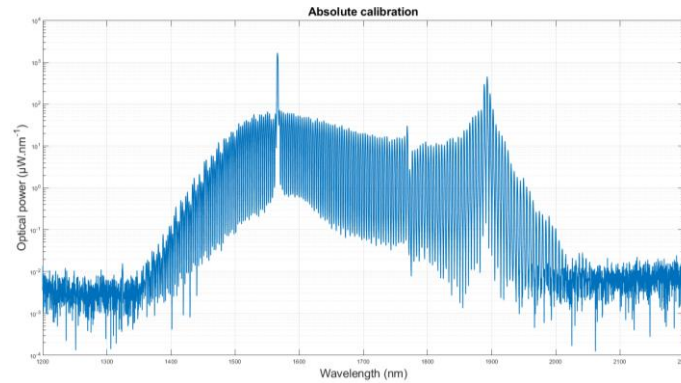


Figure 9. OFC spectrum calibrated in $\mu\text{W}/\text{nm}$ using the absolute calibration of the Bentham DTM300 double spectrometer.

The optical power contained within each comb tone was determined by integrating the measured slit function associated with each spectral line. Given that the intrinsic comb linewidth is several orders of magnitude narrower than the spectrometer resolution, each measured peak represents the instrument response function convolved with a single comb tone. The integrated line powers were corrected by a factor of three to account for the fraction of the optical beam intercepted by the spectrometer entrance slit. Analysis of all detectable comb tones demonstrated that the optical power per comb line exceeded the application requirement of $0.1 \mu\text{W}$ throughout the measured spectral range. Consequently, the optical power-per-tone requirement was successfully validated for all measurable comb tones. This was observed across the 24 comb spectrum measurements acquired.

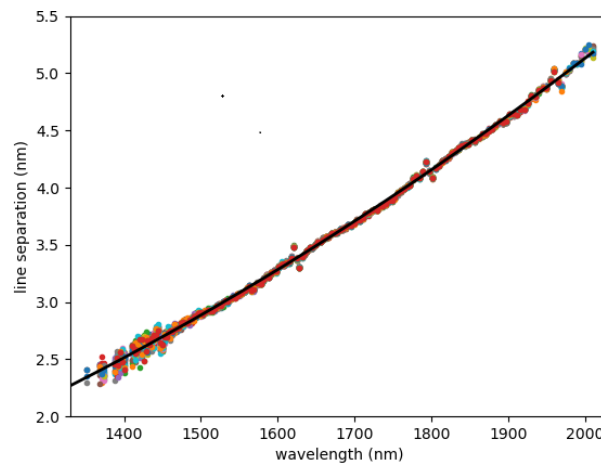


Figure 10: Comb line separation expressed in nanometres, obtained from 24 full spectrum measurements. Comparison with a theoretical line separation of 384.5 GHz.

Figure 10 shows the measured comb line spacing expressed in wavelength units, obtained from the 24 full spectrum measurements acquired throughout the validation campaign. The measured separations are compared with the theoretical line spacing expected from a comb repetition frequency of 384.5 GHz, shown by the black curve. As expected, the spacing between adjacent comb lines increases with wavelength due to the nonlinear relationship between optical frequency and wavelength. The measured line spacings closely follow the theoretical behaviour across the entire detectable spectral range, demonstrating that the generated comb maintained a uniform frequency spacing consistent with Kerr soliton operation. The observed agreement between the measured and theoretical line separations confirms a comb repetition frequency of approximately 384.5 GHz. Across the measured spectral range, the corresponding wavelength spacing remained significantly larger than the minimum application requirement of 0.23 nm derived from the VenSpec-H detector sampling characteristics. Consequently, the generated comb satisfies the comb spacing requirement and does not present a risk of spectral oversampling within the targeted instrument bands.

Finally, the wavelength stability of the comb was assessed using the corrected wavelength scale of the spectrometer. Prior to analysis, the spectrometer wavelength drift was compensated using the Hg-Ne reference measurements described previously, resulting in an estimated residual wavelength uncertainty of approximately 0.02 nm. Figure 11 presents the measured wavelength shift of all detected comb lines relative to the first measurement acquired. Over the duration of the campaign, wavelength shifts ranging from approximately +0.05 nm to -0.05 nm were observed. As the comb was

regenerated on a daily basis, these measurements primarily reflect day to day reproducibility of the system rather than short term operational stability.

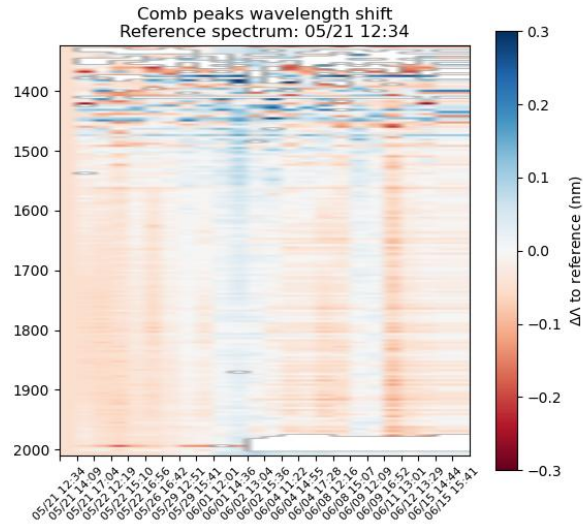


Figure 11. OFC peaks wavelength shift observed during the campaign with respect to the first measurement, using a Bentham wavelength scale virtually stable (Bentham shift corrected).

To investigate intra-day stability, multiple measurements acquired during continuous operation over 6 of the days were analysed. The spectrometer wavelength scale was verified to remain stable within approximately 0.01-0.02 nm over these measurement periods through repeated Hg-Ne reference measurements. Under these conditions, wavelength variations of the comb lines were typically observed within the range of 0.01-0.04 nm during continuous operation.

The measured wavelength variations are therefore of a similar magnitude to the residual uncertainty of the corrected spectrometer wavelength scale. Consequently, the results indicate that the comb exhibited wavelength stability at or below the measurement capability of the test facility during continuous operation.

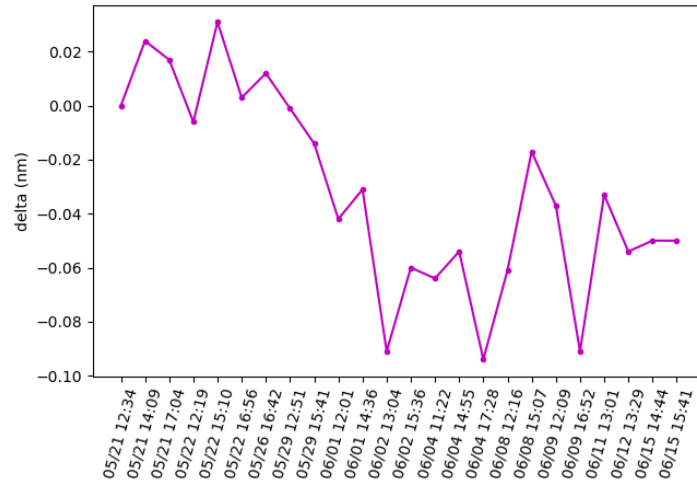


Figure 12. Final measurement of comb spectrum shift during the campaign, as deduced from the cross-correlations.

The OSIC validation campaign demonstrated the generation of a broadband Kerr soliton comb from the Microcomb Module and confirmed its potential as a calibration source for future space-based spectroscopic instruments. The generated comb successfully covered the wavelength regions corresponding to VenSpec-H Bands 3 and 4, while all measurable comb tones exceeded the minimum optical power requirement of 0.1 μ W. In addition, the measured comb line spacing significantly exceeded the minimum spacing requirement, ensuring compliance with detector sampling constraints. However, full compliance with the OSIC application requirements was not achieved. The demonstrated spectral coverage did not extend to the VenSpec-H Band 1 wavelength region, and the measured wavelength stability exceeded the target requirement of 0.005 nm. The limited spectral coverage was primarily a consequence of the dispersion profile of MRR used within the Microcomb Module, while the wavelength stability was affected by the thermal behaviour of the packaged resonator, due to a significant distance between the thermistor within the package and the MRR that was being used for comb generation. Future improvements in MRR design could enable broader comb generation and extend the spectral

coverage towards the remaining wavelength bands of interest, while enhanced package design and the implementation of closed loop feedback control with the Microcomb Module would support improvements in long-term wavelength stability.

Nevertheless, the campaign successfully validated the underlying calibration concept and demonstrated that integrated Kerr comb technology can provide a compact calibration source with suitable power and comb spacing characteristics for optical space instrument calibration applications. The broadband nature of the generated comb enables a single source to provide calibration references across multiple spectral regions, offering the potential to replace several conventional spectral lamps with a single integrated photonic device. The results of this campaign therefore demonstrate a promising path towards reduced instrument complexity, mass, and calibration subsystem overhead for future space missions, while also identifying clear development areas to improve spectral coverage and wavelength stability.

5. APPLICATION 2: TERAHERTZ GENERATION FOR HETERODYNE DETECTION

Terahertz heterodyne instruments are widely used in atmospheric science missions to measure molecular emission and absorption features with high spectral resolution. The performance of these instruments is highly dependent on the availability of stable and spectrally pure local oscillator (LO) sources capable of generating THz carriers with high frequency accuracy and stability. Conventional THz generation approaches can be limited by system complexity, power consumption, and operating conditions. OFCs provide an attractive alternative, enabling the generation of phase coherent optical tones that can be combined through optical heterodyning on a sufficiently fast photodiode to produce highly stable THz carriers. The hybrid comb architecture developed within this work combines the large free spectral range of a Kerr microcomb with the flexibility of a gain-switched optical frequency comb, enabling access to a wide range of THz carrier frequencies. Validation testing was undertaken to assess the performance of the developed THz generation architecture against the application requirements. Testing focused on verifying compliance with the key application requirements, including carrier frequency, linewidth, frequency stability, and frequency accuracy.

The validation campaign was carried out using a Rohde & Schwarz ZVA24 Vector Network Analyser (VNA) equipped with ZC1100 frequency extension heads. The measurement system provided frequency coverage from 750 GHz to 1100 GHz through harmonic multiplication of a local oscillator signal operating in the 15.6-22.9 GHz range. The generated THz signal was emitted from the waveguide-integrated photodiode antenna (WIN-PD) and transferred to the receiving extension head using an alignment system comprising two off-axis parabolic mirrors. This arrangement enabled efficient free-space coupling of the THz radiation from the WIN-PD to the measurement system for characterisation of the generated carriers.

The VNA was calibrated with the frequency extension heads installed in the quasi-optical measurement system to ensure that the complete measurement path was included within the calibration reference planes. A UOMS (Unknown Through, Offset Short, Match, Short) calibration was selected in preference to a conventional TOMS calibration, as it avoided the need to physically reconfigure the waveguide setup to realise a through standard. This minimised disturbance of the RF and LO signal paths and reduced the risk of introducing calibration uncertainties, particularly in phase measurements. The existing quasi-optical 4f relay system, comprising two Pickett-Potter horns and four gold-coated mirrors, was used as the Unknown Through standard. This arrangement satisfied the reciprocity and low-loss requirements of the UOMS calibration methodology, with transmission losses arising primarily from residual optical aberrations and mirror absorption. To ensure reliable phase unwrapping during calibration, 3501 frequency points were used across the measurement band, corresponding to a frequency step of 100 MHz. For a propagation distance of approximately 0.7 m, this resulted in an inter-point phase change below 90° , satisfying the calibration requirements. The Short, Offset Short, and Match calibration measurements were performed with the horns removed, while the Unknown Through measurement was acquired with the full quasi-optical system in place. Throughout the procedure, all critical RF and LO interconnections were left undisturbed to preserve measurement consistency. Following calibration, the measured transmission response exhibited the expected near-unity behaviour across the operating band, with the exception of identifiable atmospheric water vapour absorption features.

Before evaluating THz carrier generation using the hybrid optical frequency comb architecture, the performance of carriers generated through photomixing of tones from the Kerr soliton comb alone was investigated. A Kerr soliton comb was generated using the Microcomb Module, with the resulting optical spectrum shown in Figure 4 (a). A wavelength-selective switch (WSS) was then used to isolate two comb lines from the generated spectrum, while all remaining comb lines were suppressed. The selected tones were subsequently amplified to a total optical power of 20 mW using an EDFA. The comb lines were chosen such that the resulting THz carrier frequency would fall within the measurement range of the VNA and frequency extension heads. Previous measurements had established a comb spacing (or free spectral range) of 384.5 GHz for the Kerr soliton comb. Consequently, two comb lines separated by two free spectral ranges were selected, corresponding to a target carrier frequency of approximately 769 GHz. The filtered and amplified optical tones used for photomixing are shown in Figure 13. The optical signal was subsequently coupled into the WIN-PD, where photomixing of the filtered comb lines generated the THz carrier. The emitted THz radiation was then characterised using the VNA.

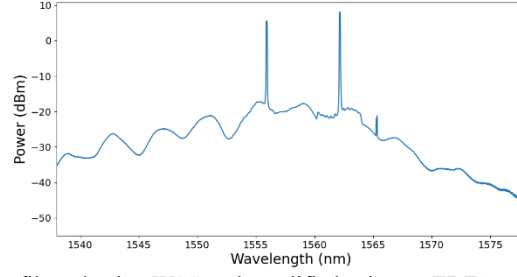


Figure 13. Kerr soliton comb lines filtered using WSS and amplified using an EDFA.

Figure 14 (a) shows the THz carrier measured by the VNA. The measurements were performed using the VNA clear-write acquisition mode, allowing individual sweeps to be observed without trace averaging. As the carrier was generated from two tones originating from the same Kerr soliton comb, the intrinsic linewidth was expected to be extremely narrow. Consequently, the multiple features observed in the VNA trace are attributed to small variations in the carrier frequency occurring during the measurement period rather than the intrinsic linewidth of the generated THz carrier. To determine the carrier frequency, the measurement was repeated ten times. During post-processing, all peaks located more than two standard deviations above the noise floor were identified and their frequencies recorded. A histogram of the detected peak frequencies is shown in Figure 14 (b), where a bin width of 10 kHz was selected to match the VNA resolution bandwidth used during the measurements. From this analysis, the carrier frequency was determined to be 769.04146 GHz.

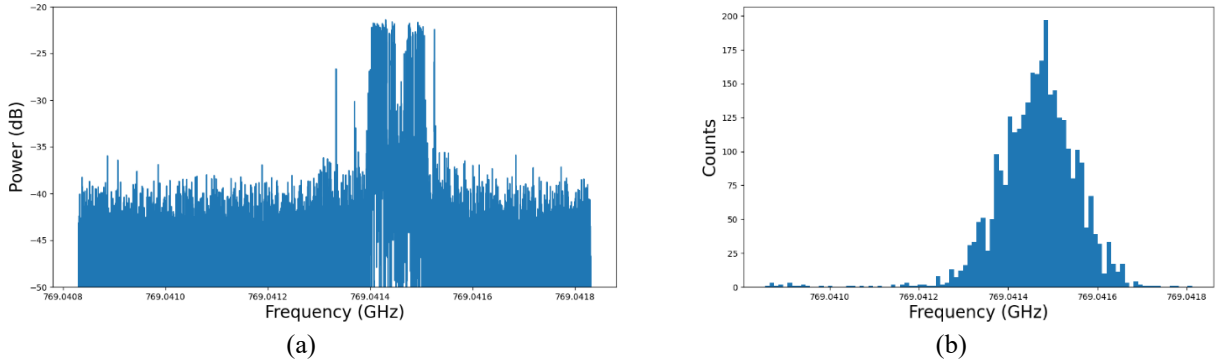


Figure 14. (a) Measurement of the signal using the VNA and (b) histogram showing the occurrence of peak frequencies detected across repeated VNA sweeps.

This value is consistent with the results obtained during the OSIC validation campaign, where the spacing between adjacent Kerr comb lines was measured to be approximately 384.5 GHz. The measured carrier frequency corresponds to approximately twice this spacing, indicating operation using comb lines separated by two free spectral ranges. The difference between the measured carrier frequency and the target frequency of 769.1 GHz is approximately 58.5 MHz, demonstrating compliance with the frequency accuracy requirement of < 100 MHz.

While the intrinsic linewidth of the generated carrier could not be measured independently of the observed carrier frequency fluctuations, the total observed spectral spread remained below 1 MHz. As the application requirement is specified as a maximum allowable linewidth of 1 MHz, the measured response is consistent with compliance. However, the present measurements do not permit separate quantification of the intrinsic linewidth and carrier frequency instability, and additional investigations would be required to fully characterise the spectral purity of the generated signal.

To investigate the frequency stability of the signal further, the maximum hold function on the VNA was used. This retains the highest measured signal level at each frequency across multiple sweeps. Figure 15 shows the maximum hold measurements obtained after integration times of 10, 30, 300, and 600 seconds, respectively. These results were extracted from a single continuous measurement, with snapshots of the maximum hold trace recorded at the specified time intervals. The maximum frequency drift remains below the 1 MHz requirement in all cases, and was approaching convergence during the measurement period. The frequency variation observed within these measurements is due to thermal instability of the MRR within the Microcomb Module. Improved packaging of the MRR, as well as implementation of closed loop feedback control will reduce the instability observed.

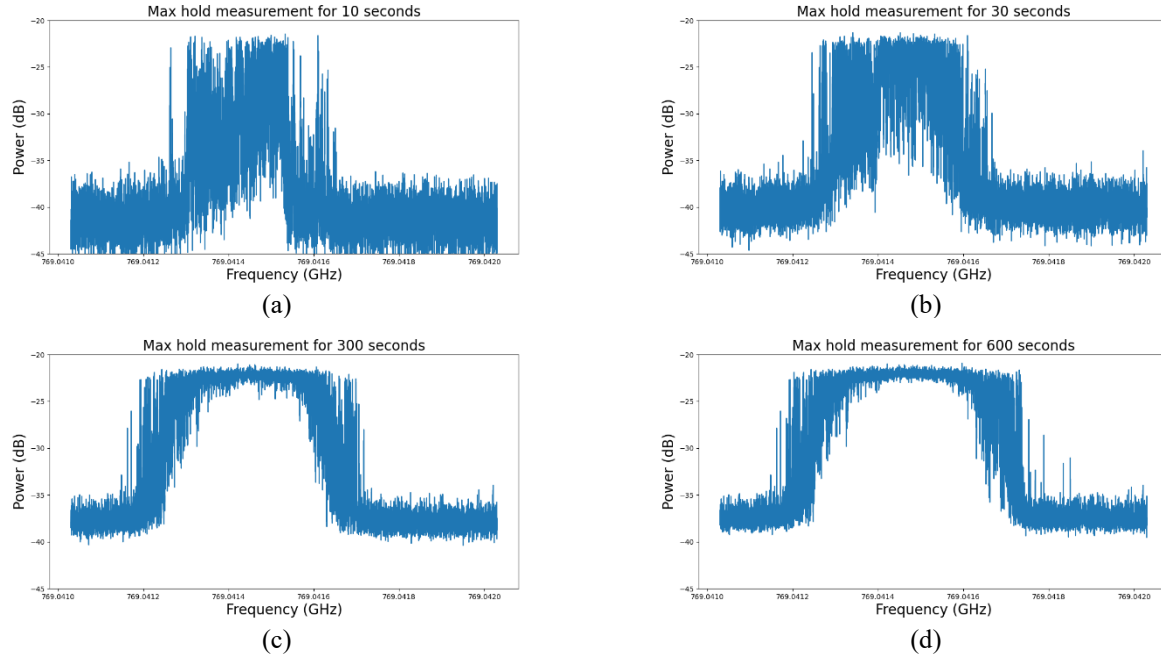


Figure 15. Maximum hold measurements recorded at time intervals of (a) 10, (b) 30, (c) 300 and (d) 600 seconds.

To increase the range of accessible THz carrier frequencies, the Terahertz Module was incorporated to realise a hybrid comb architecture combining the large free spectral range of the Kerr soliton comb with the flexibility of a gain-switched comb. The addition of the gain-switched comb followed the same format as in functional verification testing. Once again, the Kerr soliton comb was generated from the Microcomb Module. The output of the Microcomb Module was passed to the input of the Terahertz Module, which contained the components required for the integration of the gain-switched comb. Once light entered the Terahertz Module, a 50:50 splitter was used to split the comb light equally between two optical paths. One path contained the variable optical filter and EDFA. The variable optical filter was set to central wavelength of 1538.4 nm with a bandwidth of 0.4 nm. The second path contained the DFB laser which was to be used as the slave for gain-switching. The wavelength of the DFB was aligned to match the wavelength of one of the lines from the Kerr soliton comb. This allowed for phase synchronisation of the two comb sources via optical injection locking. The gain-switching frequency was set to 12.5 GHz and applied using an external signal generator. The output was then recombined and then amplified to 20 mW using an EDFA before passing from the Terahertz module. Figure 16 shows the optical output from the Terahertz module, showing the Kerr comb line at 1538.4 nm and the injection locked gain-switched comb centred around 1545 nm. The optical signal was then directed onto the WIN-PD, where photomixing of the optical beat signal took place.

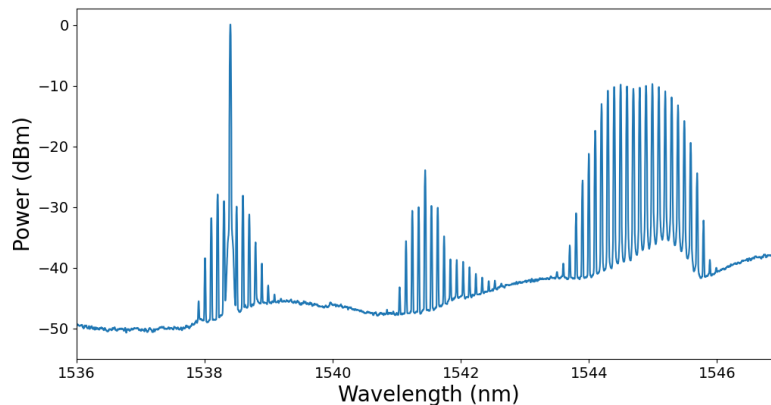


Figure 16. Optical spectrum showing the filtered Kerr comb line and the injection locked gain-switched comb using for optical heterodyning.

Due to the low SNR of the detected signal, maximum hold measurements were used to improve the visibility of weak spectral components. By retaining the maximum value recorded at each frequency over multiple sweeps, the signal could be more readily distinguished from the noise floor. However, this approach also accumulated noise peaks and transient signals, making it more suitable for signal detection than for accurate power or SNR measurements. Figure 17 (a) – (d)

shows the signals measured, starting 769.0435 GHz and increasing in steps of 12.5 GHz to align with the gain-switching frequency. The orange trace represents the maximum hold measurement with the signal turned off in order to determine the noise floor of the measurement. The blue trace represents the maximum hold measurement over 3 minutes with the signal turned on, taken subsequently to the orange trace. A significantly lower signal to noise ratio is observed in the measurements shown in Figure 17 (a) – (d), than those shown in Figure 14 or Figure 15. While these measurements show the presence of the signal, the SNR is too weak to proceed with any further characterisation. The reduced SNR is due to the reduced optical power of the gain-switched comb lines, compared to the previous measurement. When using adjacent Kerr soliton comb lines, the power per line was in the range of 5 - 8 dBm. When using the Kerr soliton comb line and gain-switched comb, the power was significantly lower, down to -10 dBm per line for the gain-switched comb. Increased optical power is required in order to improve the SNR of the subsequent photomixed signal measured on the VNA. However, the max hold measurements shown in Figure 17 show that greater flexibility can be achieved through the hybrid comb approach, provided that higher optical power per line can be reached, including exceeding the 800 GHz frequency requirement.

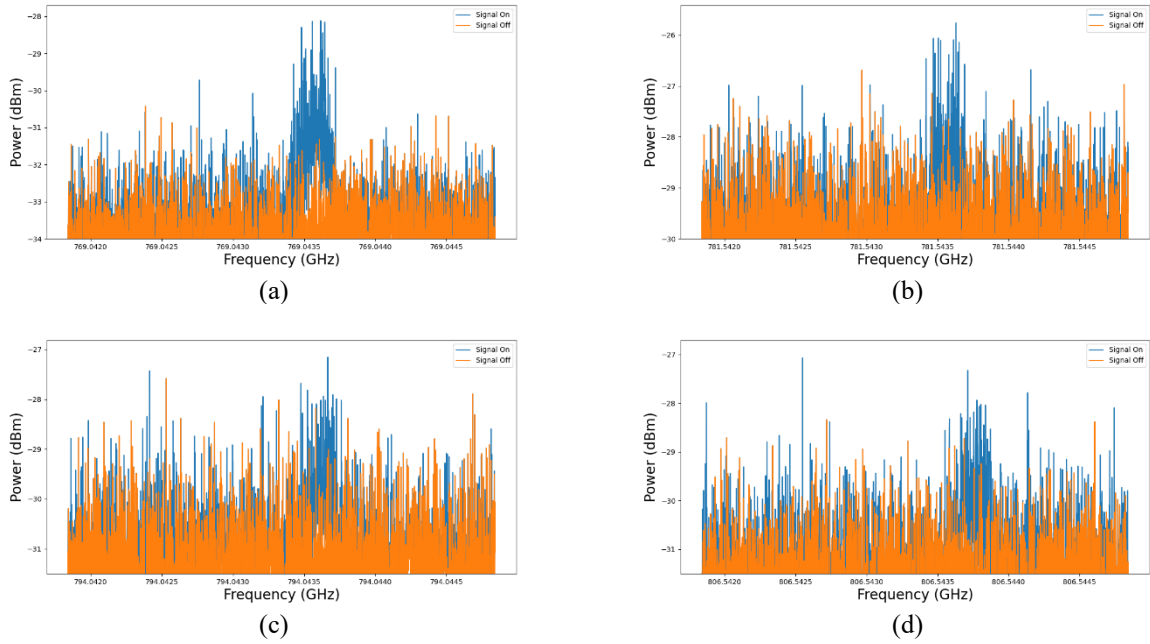


Figure 17. Electrical spectra showing maximum hold measurements of the carriers generated from the hybrid comb architecture.

6. CONCLUSIONS

This work has demonstrated the potential of optical frequency comb technology for two space based applications: Optical Space Instrument Calibration (OSIC) and Terahertz Generation for Space Heterodyne Instrumentation (THZG). Two breadboard demonstrators were developed and validated, comprising a Kerr soliton Microcomb Module and a Terahertz Module based on an injection-locked gain-switched optical frequency comb architecture. For the OSIC application, the generated Kerr soliton comb provided broad spectral coverage encompassing the VenSpec-H Bands 3 and 4 wavelength regions, while all measurable comb tones exceeded the required optical power threshold and the measured comb spacing satisfied detector sampling constraints. Although the target wavelength stability and full spectral coverage requirements were not achieved, the results successfully validated the underlying calibration concept and demonstrated the potential for a single integrated comb source to replace multiple conventional calibration lamps.

For the THZG application, THz carrier generation was successfully demonstrated using both Kerr comb only and hybrid comb architectures. The generated carriers satisfied the frequency accuracy and linewidth requirements, while the hybrid approach combined the large free spectral range of the Kerr soliton comb with the frequency agility of the gain-switched comb to enable access to a wider range of THz carrier frequencies. While the SNR of the generated carriers from the hybrid comb approach was limited, this can be improved in the future by increasing the SNR of the optical signal used for photomixing. Overall, the validation campaigns demonstrate the potential of optical frequency comb technologies for future space instrumentation.

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