

Frequency Combs for Space Applications

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ABSTRACT

A compact, low-SWaP (size, weight, and power), radiation-tolerant, and vacuum-compatible space frequency comb has been developed for optical clocks in orbit. The instrument represents a key enabling technology for coherent optical-to-RF (and RF-to-optical) frequency synthesis and frequency dissemination in distributed space-based systems. The design has been optimized for robustness, modularity, and environmental endurance, with delivery of flight models scheduled for late 2026 in preparation for in-orbit demonstration campaigns on the COMPASSO and CRONOS missions foreseen for 2027–2028. The opto-electronic configuration integrates a fiber-based femtosecond mode-locked laser, low-noise split-stage fiber amplifiers, and a miniaturized nonlinear broadening module, all housed within a mechanically and thermally stabilized optical bench with dimensions $35\text{ mm} \times 133\text{ mm} \times 129\text{ mm}$. The electronics unit includes an ultra-low phase-noise microwave reference chain, mixed-signal servo controllers, redundant pump laser modules, and optional servo controllers for lasers referenced by spectroscopy, implemented on an FPGA basis. The modular architecture has been demonstrated in a lab demonstrator for the CRONOS mission, combining the comb with an external rubidium two-photon spectroscopy reference. The frequency-stability performance of the comb’s 10 MHz microwave output has been characterized through phase noise and Allan deviation measurements: a power-law noise model fit to the measured single-sideband phase noise predicts the Allan deviation to within a factor of 1.1–1.3 for averaging times up to 100 s, in agreement with measured values, while longer averaging times show the expected additional suppression from the repetition-rate servo loop.

Keywords: frequency comb, optical clock, space qualified

1. INTRODUCTION

An optical frequency comb is generated by a train of ultrashort laser pulses whose spectrum consists of a series of discrete, perfectly equidistant frequency modes. The comb is fully determined by only two radio-frequency parameters, the pulse repetition rate f_{rep} and the carrier-envelope offset frequency f_{ceo} , both of which can be measured and stabilized against a microwave or optical reference. Once self-referenced, the comb acts as a phase-coherent gearwheel between the optical and microwave domains, enabling counting of optical frequencies with the precision and accuracy of the reference against which it is stabilized. Over the last two decades this capability has transformed the comb from a laboratory metrology tool into a widely used technology underpinning optical clocks, precision spectroscopy, and coherent frequency dissemination.¹

Several distinct laser architectures can be used to generate an optical frequency comb, and the choice of architecture has a direct impact on how small, robust, and radiation-tolerant the resulting instrument can be made. Mode-locked solid-state lasers offer high pulse energy and low intrinsic noise and can be built as compact, radiation-hard sources, as demonstrated by a diode-pumped solid-state femtosecond comb qualified for space use;² however, they are less amenable to all-fiber integration and typically require free-space alignment that adds sensitivity to mechanical and thermal disturbance. Fiber-based mode-locked lasers, in particular erbium-doped fiber lasers operating in the telecommunications band, build on mature, radiation-tolerant fiber components^{3,4} and can be assembled as monolithic, all-polarization-maintaining systems with ultra-low noise performance,^{5,6} making this architecture the current workhorse for space-qualified frequency combs and the basis of the instrument presented in this work. Microresonator-based (Kerr) combs use a continuous-wave laser coupled to a high- Q optical microresonator to generate a comb directly on a chip-scale photonic platform,^{7–9}

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offering the most compact and potentially wafer-scale-integrable form factor and enabling low-noise microwave generation;^{10,11} full self-referencing and octave-spanning operation of microcombs at flight-qualified noise and power levels, however, remain more challenging than for fiber systems. Electro-optic (EOM) combs generate comb lines directly from a continuous-wave laser using cascaded electro-optic phase and amplitude modulators, avoiding mode-locking altogether and offering a mechanically simple, vibration-insensitive architecture with an electronically tunable line spacing; the trade-off is a comparatively narrow and non-flat native spectrum, which typically must be broadened and amplified to reach the bandwidth required for full self-referencing.

Beyond the choice of generation architecture, robust operation in a space environment requires that the comb's two radio-frequency degrees of freedom remain reliably locked under mechanical, thermal, and radiation loads. Menlo Systems has addressed this by replacing bulkier feed-forward, acousto-optic stabilization schemes with a fast electro-optic modulator acting directly on the pump diode current or intracavity phase, enabling rapid, wide-bandwidth control of f_{ceo} and, in combination with an all-polarization-maintaining erbium fiber design, ultra-low phase-noise comb operation.^{12,13} This architecture has been progressively hardened and miniaturized for spaceflight, from an early sounding-rocket demonstration of a frequency comb and precision spectroscopy experiment in space¹⁴ to the compact, vacuum-compatible dual-comb system flown on under the FOKUS II campaign.¹⁵ The instrument presented here builds on this technology base, with the specific requirements, architecture, and qualification results for the COMPASSO and CRONOS missions discussed in the following sections.

2. SYSTEM

The systems engineering of a space-grade optical frequency comb (OFC) must accommodate a wide range of mission requirements and constraints. To serve missions spanning human spaceflight, microsatellite platforms, and long-duration space-grade deployments within a single product line, the instrument has been designed as a compact, internally modular system with exchangeable electronics that can be adapted to each mission's needs. Individual modules are connected via an internal bus and can be added or removed without altering the underlying architecture. Major interfaces – power, communications, RF I/O, and optical inputs – are predefined, while customer-specific modules controlling external lasers and/or spectroscopy add their own front-plate interface connectors. The comb's fiber-optics compartment comprises a standardized comb-oscillator tray and an amplifier tray, the latter adaptable to the continuous-wave (CW) wavelength that the comb is required to control or lock to. The system SWaP starts from 7.5 liter, 6.5 kg, and 35 W, with the exact volume and power depending on the number and power consumption of the inserted custom modules.

Particular attention has been paid to the cooling concept under vacuum, which is based on one or more cold plates attached to the outer system walls. The primary cold plate is attached to the bottom of the optics module, which requires the highest temperature-control accuracy, stable to within 1 mK. To reach this precision, the fiber tray is temperature-controlled using thermoelectric coolers whose hot side is connected to the cold plate. Thermal stabilization of the electronic modules, which require efficient cooling of heat dissipating PCB components, is achieved through a thermally conductive system frame that conducts heat from all PCBs via aluminum system walls to the attached cold plates.

Long-term radiation tolerance is a further important consideration, depending on the mission environment. While radiation-hardness data for qualified EEE components is generally available, fiber-optic and photonic components require more careful evaluation to guarantee their lifetime over the duration of the envisaged missions: many fibers and optical glasses degrade under highly energetic radiation, and electro-optic components such as diode lasers and photodiodes are likewise sensitive to irradiation. In this respect, we have verified the radiation tolerance of a fiber-based frequency comb laser up to 1 kGy,¹⁶ and we use high-reliability components with flight heritage wherever available. An additional, extensive component test program is applied to components whose space reliability has not yet been confirmed.

3. RESULTS AND CONCLUSION

The results of this work are illustrated in Figs. 1a and 1c, which shows an example of the comb integrated into the payload of the CRONOS mission. The CRONOS comb represents the upper end of the system's SWaP

range, as it operates not only the internal comb but also the external CW laser modules and the rubidium two-photon spectroscopy module.¹⁷ The precursor lab demonstration model of the system is also shown with the front plate removed in Fig. 1d, revealing the modular inner architecture, while the accompanying block diagram Fig. 1b highlights the central role of the electronics unit in controlling and operating both the comb and the reference spectroscopy. This architecture supports close interaction between the optical reference and the comb and lays the groundwork for a future, monolithically integrated space optical clock. For the case of two-photon Rb spectroscopy, it appears quite feasible to integrate the spectroscopy unit, the 778 nm MOPA, and the modulation EOM into a slightly extended comb housing. For more complex atomic references – ranging from iodine modulation-transfer spectroscopy to more advanced MOT- or ion-clock-based systems – integration into the comb becomes less attractive, as these technologies are considerably bulkier; for such systems, the stand-alone comb unit remains the better and more flexible design option.

In addition to this system-level integration, the frequency-stability performance of the comb’s 10 MHz reference output was characterized in detail through phase noise and Allan deviation measurements. The single-sideband phase noise $L(f)$ was measured over offset frequencies from 1 Hz to 100 kHz and fit to the standard IEEE power-law noise model¹⁸

$$S_\phi(f) = \sum_{i=-4}^0 h_i f^i, \quad (1)$$

where the five terms correspond to random-walk, flicker, and white frequency modulation (f^{-4} , f^{-3} , f^{-2}) and flicker and white phase modulation (f^{-1} , f^0), respectively. A discrete spur observed at 1 kHz, attributed to a servo-loop artifact, was excluded from the fit; the remaining data were well described by only three non-zero terms (white FM, flicker PM, white PM), as shown in Fig. 2.

Table 1 lists the fitted power-law coefficients h_i of $S_\phi(f)$ together with the corresponding fractional-frequency PSD coefficients h_α , obtained via $S_y(f) = (f/\nu_0)^2 S_\phi(f)$ with carrier frequency $\nu_0 = 10$ MHz.

Table 1: Fitted IEEE power-law noise coefficients for the 10 MHz output ($\nu_0 = 10$ MHz), excluding the 1 kHz spur.

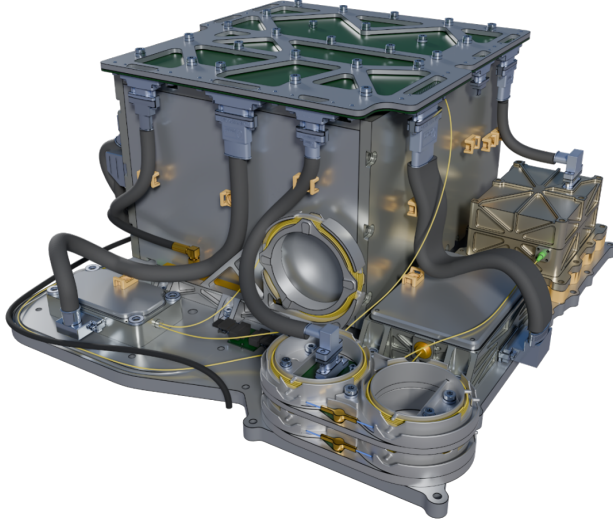
Noise type	$S_\phi(f)$ exponent i	h_i	$S_y(f)$ exponent α	h_α
Random walk FM	−4	0	−2	0
Flicker FM	−3	0	−1	0
White FM	−2	7.82×10^{-12}	0	7.82×10^{-26}
Flicker PM	−1	9.29×10^{-11}	1	9.29×10^{-25}
White PM	0	2.10×10^{-15}	2	2.10×10^{-29}

These coefficients were subsequently converted to the Allan deviation $\sigma_y(\tau)$ using the standard closed-form expressions for each power-law noise type.¹⁹ This frequency-domain prediction was compared against Allan deviation values obtained independently from a time-domain measurement of the same 10 MHz signal in a comb-comb comparison (Fig. 3).

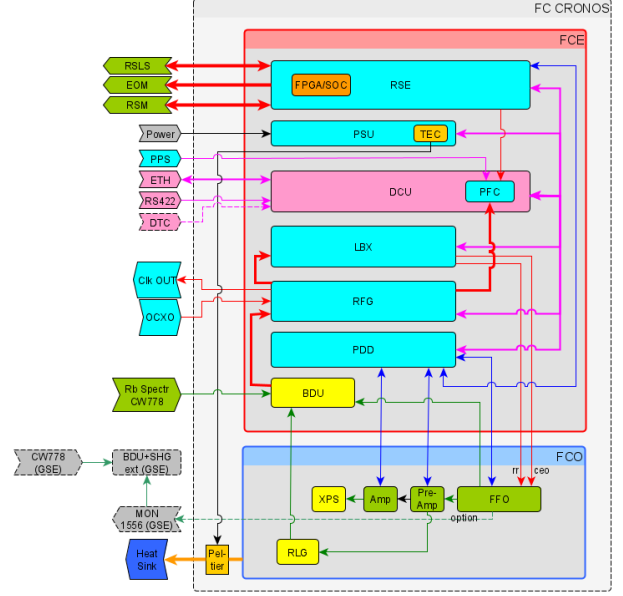
For averaging times $\tau \leq 100$ s the prediction derived from $L(f)$ agrees with the direct time-domain measurement to within a factor of 1.1-1.3, confirming that the frequency- and time-domain characterizations of the short-term noise are mutually consistent. For $\tau > 100$ s, the measured Allan deviation falls increasingly below the $L(f)$ -based prediction, reaching a factor of about 2 at $\tau = 1000$ s and up to a factor of 5 at $\tau \approx 4 \times 10^4$ s. This deviation is attributed to the repetition-rate stabilization loop, which actively suppresses random-walk and flicker frequency noise on time scales beyond its servo bandwidth – an effect not captured by the free-running noise model extrapolated from $L(f)$ data limited to offset frequencies above 1 Hz. This comparison illustrates that while phase noise measurements alone can reliably predict short-term stability, closed-loop long-term stability must be verified through direct Allan deviation measurement.

4. APPLICATIONS AND OUTLOOK

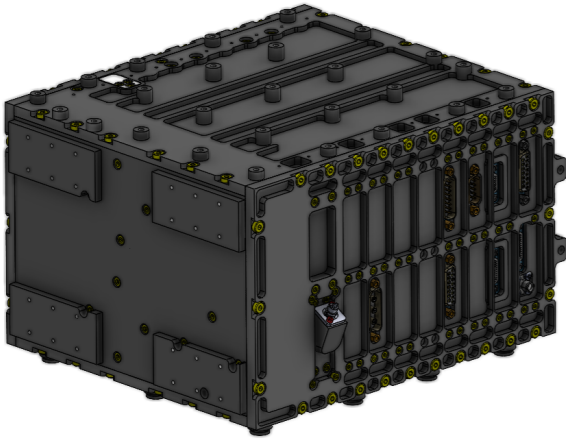
Space-qualified frequency combs enable a broad range of applications that rely on precise, drift-free coherent links between the optical and microwave domains. The most immediate application is the optical-to-RF and



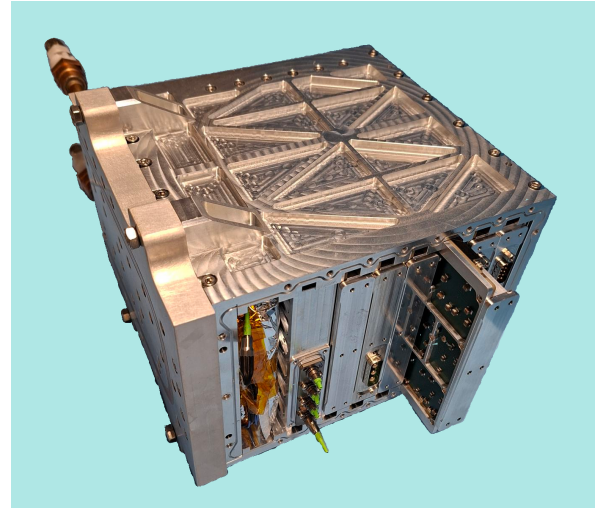
(a) CRONOS payload



(b) CRONOS comb block diagram



(c) CRONOS FM comb design currently under manufacturing



(d) CRONOS lab development model (ROSC) attached to a coldplate with its frontplate removed

Figure 1: CRONOS space comb design for a 2-photon Rb referenced optical clock payload

RF-to-optical synthesis required for space-borne optical clocks, where frequency combs provide the clockwork linking an ultra-stable optical reference to a microwave output usable by conventional timing and navigation hardware.²⁰ This capability is directly relevant to next-generation satellite navigation systems and to tests of fundamental physics that require long-term frequency stability in orbit, such as searches for variations of fundamental constants or relativistic frequency shift measurements.

Beyond clock synthesis, frequency combs support a number of distinct measurement techniques. Dual-comb ranging allows fast, unambiguous absolute distance measurements without moving parts, with sub-micron precision demonstrated in real time^{21,22} and further improvements in acquisition speed and sensitivity through Kerr-soliton-based and quantum-limited approaches.^{23,24} A dedicated dual-comb ranging payload has recently demonstrated sustained on-orbit operation aboard the Chinese Tiangong space station,²⁵ underlining the grow-

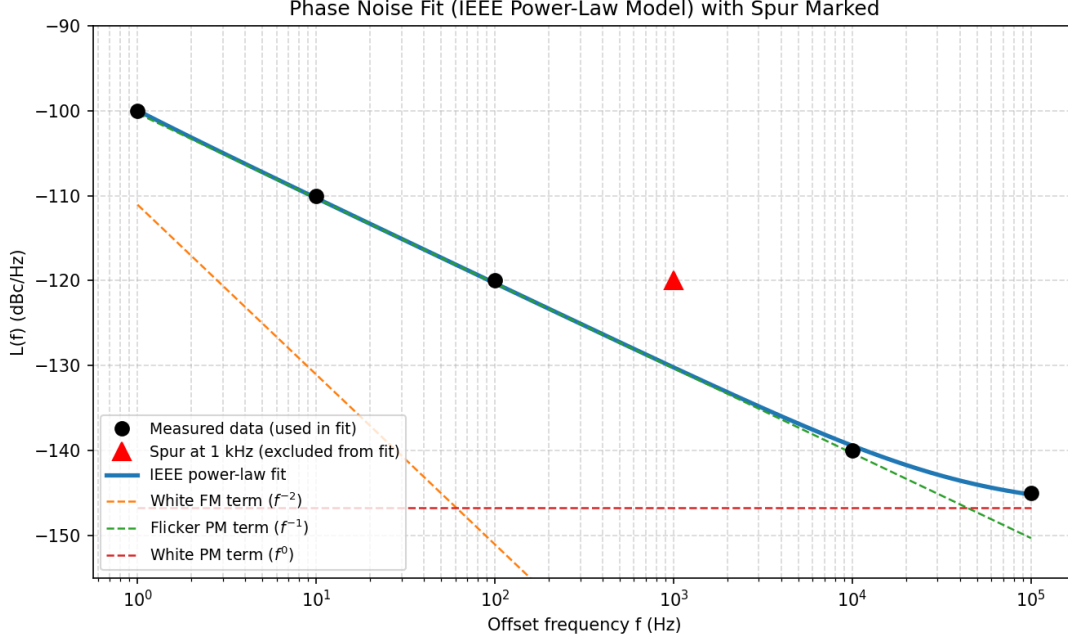


Figure 2: Projected single-sideband phase noise $L(f)$ of the 10 MHz output (black circles) of an optically locked space-comb with the IEEE power-law fit (blue) and the individual noise contributions (dashed). The spur at 1 kHz (red triangle) was excluded from the fit.

ing maturity of comb-based ranging for formation-flying and inter-satellite metrology applications. Related time-frequency (TF) links are a key enabling technology for coherent time and frequency dissemination across distributed space-based sensor networks,²⁶ and are directly applicable to future gravimetry missions, where time-frequency signal transmission techniques are emerging as a means of determining the Earth’s gravity potential,²⁷ as well as to atom-interferometry missions requiring common time references between remote platforms, building on recent demonstrations of ultracold-atom interferometry in space.²⁸ Frequency-comb-based approaches are furthermore being explored for gravitational-wave detection in the deci-Hz band.²⁹

Frequency combs also enable a range of spectroscopic and remote-sensing applications relevant to earth observation. Airborne trials have shown that a rugged, self-referenced frequency comb can serve as an in-flight frequency reference for an integral-path differential-absorption LIDAR system measuring atmospheric CO₂ and CH₄,³⁰ a capability directly transferable to spaceborne greenhouse-gas monitoring missions. More broadly, dual-comb spectroscopy offers drift-free, absorption-model-based calibration for precision trace-gas monitoring,³¹ while comb-calibrated astronomical spectrographs (astrocombs) have become an established tool for high-resolution spectrometer calibration, e.g. in exoplanet radial-velocity searches.³² The same comb’s reference chain can generate ultra-low-phase-noise microwave signals,^{33–35} which are also of interest for microwave radar applications, where improved spectral purity can enhance Doppler resolution and ranging accuracy.

Building on the design presented here, several in-orbit demonstration missions are foreseen. A space comb will be flown on the COMPASSO mission, a DLR technology demonstrator for optical clock technologies,³⁶ another one on the CRONOS (Compact Rubidium Oscillator for Navigation systems Onboard a Satellite) mission, a micro-satellite payload combining a compact rubidium two-photon optical frequency reference with a Menlo Systems frequency comb to demonstrate an optical clock in low Earth orbit. The CRONOS rubidium reference is driven by a novel monolithically integrated extended-cavity diode laser at 778 nm,³⁷ and its two-photon spectroscopy scheme, building on earlier compact rubidium clock demonstrations,^{14,38} has been developed specifically for this payload.¹⁷ Such missions serve as pathfinders towards the adoption of frequency-comb-based optical clock and synchronization technology in operational systems, including next-generation Galileo satellites, where improved clock and timing performance is expected to directly benefit positioning accuracy. Together, these

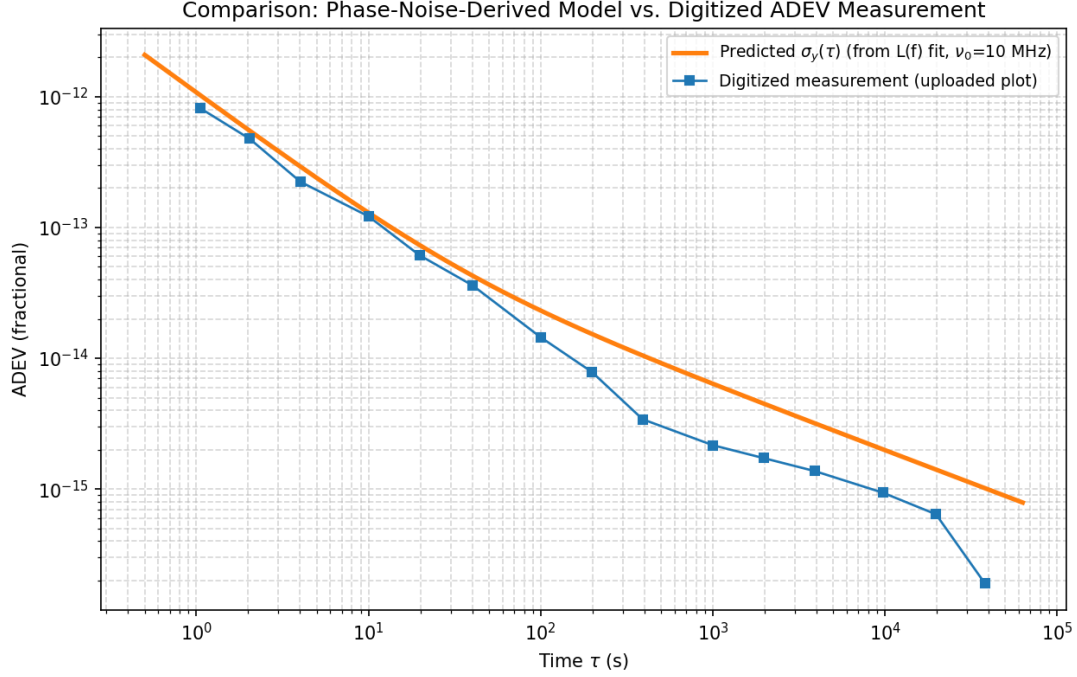


Figure 3: Allan deviation of the 10 MHz output predicted from the phase noise fit (orange) compared with the directly measured Allan deviation (blue squares).

in-orbit validation (IOV) activities mark a first step towards the routine use of space-borne frequency combs in future geodesy, navigation, earth-observation, and fundamental-physics missions.

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