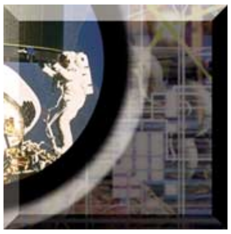

Syntonics LLC: APL-Developed Technology Makes Its Commercial Debut

Joseph J. Suter, Larry J. Crawford, Bruce G. Montgomery, and Wayne E. Swann

Syntonics LLC, the first new commercial start-up company made possible through the transfer of technology developed at APL, was created in December 1999. This completely independent company was formed to build and sell ultrastable oscillators, an advanced technology pioneered by APL during the early space program. The Laboratory transferred the technology to Syntonics under an exclusive licensing agreement, thus giving a broader range of customers access to a proven, mission-critical product that was previously available only to the U.S. government.

INTRODUCTION

Ultrastable quartz oscillators (USOs) are extremely precise, reliable, and stable clock-like timekeeping devices used onboard spacecraft (Fig. 1). They ensure long-term, dependable spacecraft operations, generating ultrastable frequency and time signals on a wide spectrum of platforms: low-Earth orbit satellites, geosynchronous satellites, and deep space probes. APL-developed oscillator technology had its debut in the 1960s on Transit, a constellation of satellites that was part of the Navy Navigation Satellite System, the forerunner to the Global Positioning System.[1–3] Over the last 40 years, the technology has continued to advance and mature at the Laboratory. To date, more than 400 USOs have been produced for a variety of government-sponsored space missions. However, until this APL-developed technology was licensed to Syntonics LLC[4] in 1999, the devices, produced one at a time, were available only to the U.S. government, since APL, by policy, does not perform commercial manufacturing and does not sell directly to industry.

Historically, piezoelectric quartz crystal oscillators have been widely used in satellite communication and guidance systems.[5,6] The system performance of satellites requires USOs with superior timekeeping stability, low system noise levels, and excellent phase noise characteristics.[2,5] Compared with atomic-based time and frequency sources (Fig. 2), quartz crystal oscillators offer certain advantages, e.g., simplicity of design, ruggedness, lower development cost, and greater mean time between failure.[2,6]

Pierre and Jacques Curie discovered the piezoelectric effect in 1880 while studying the physical properties of natural quartz and rochelle salt. However, it was the publication of *Lehrbuch der Kristallphysik* by Voight (1910)[7] and later *Piezoelectrizitat des Quarzes* by Scheibe (1938)[8] that initiated systematic theoretical and experimental studies of piezoelectricity. Piezoelectricity has been observed in a variety of natural and synthetic crystalline materials including quartz,[6] which forms the basis for the precise

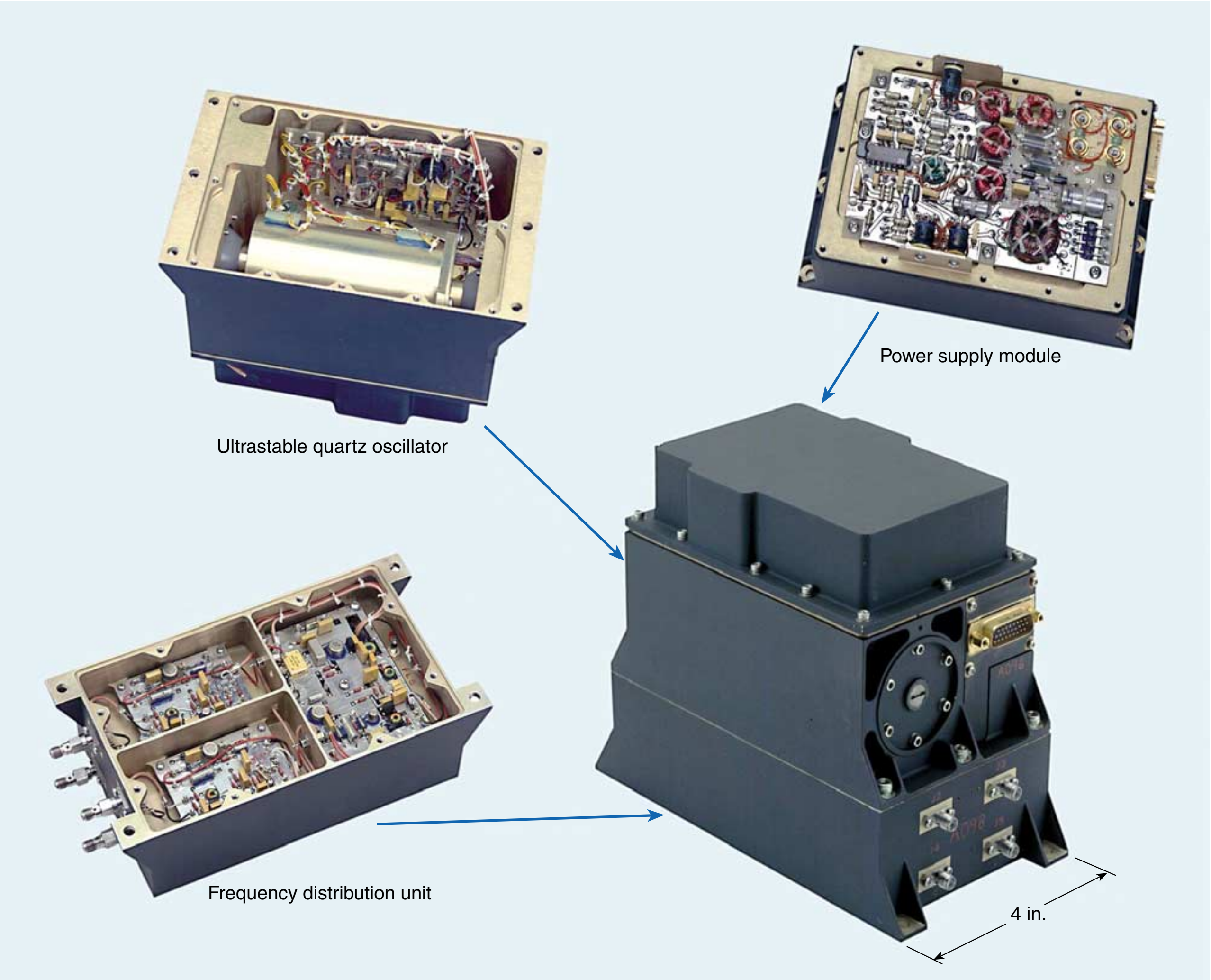

Figure 1. Exposed view of an APL-developed USO.

operation of the APL oscillators to be manufactured by Syntonics LLC.

Highly stable quartz crystal resonators onboard spacecraft must have low susceptibility to magnetic and electric fields, *g*-forces, and ionizing radiation. These requirements motivated the development of reliable screening procedures to evaluate quartz crystals prior to the manufacture of quartz crystal oscillators. The increasing demand for high-performance quartz crystals in a space environment has spurred continuous efforts to reduce their sensitivity to these external physical phenomena.[2,9]

Consider, for example, the quartz crystal oscillator's sensitivity to space radiation.[9–12] In many space missions the frequency stability requirements for resonators are specified for sampling periods shorter in duration than one orbit (Fig. 3). Hence, even though the total accumulated doses over a complete mission can exceed 10^4 rad, the resonator system requirements deal with frequency shifts on a per-orbit basis. Thus, examining the radiation sensitivity of quartz crystal resonators to large doses ($>10^4$ rad) will not reveal their true radiation susceptibility to low doses.[10]

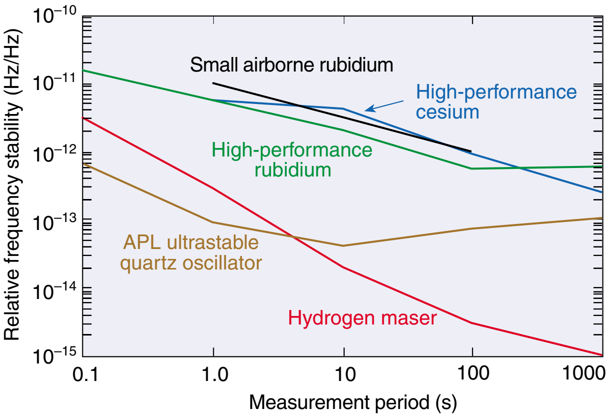

Figure 2. Performance of frequency sources in the time domain. The quartz crystal oscillator offers the best stability between 1 and 1000 s. The more complex atomic frequency standards are better suited for applications with measurement intervals >1000 s.

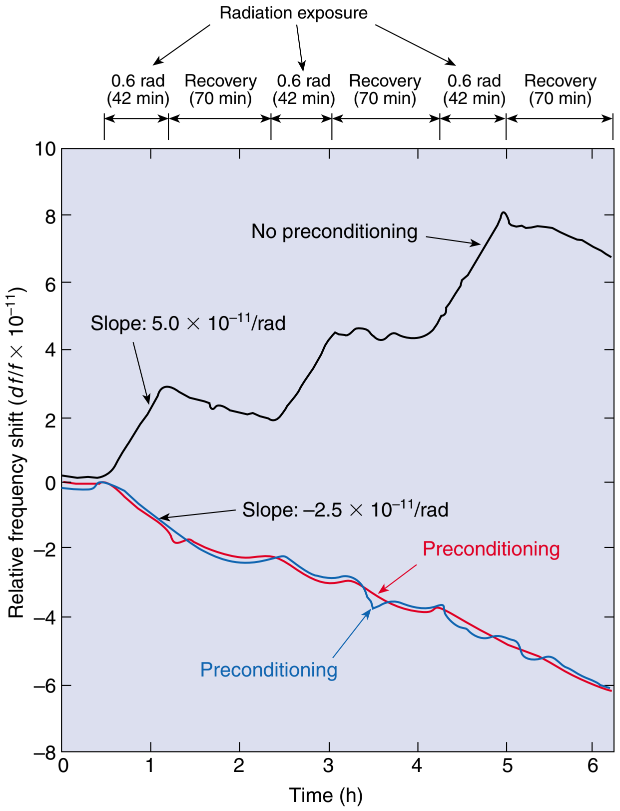

Figure 3. Response of a quartz crystal oscillator to simulated TOPEX orbit space radiation effects while traversing the South Atlantic Anomaly at 1440 km (black curve) compared with data obtained using two simulated space radiation sources: 20 krad Co^{60} (red curve, preconditioning) and 40 krad Co^{60} (blue curve, preconditioning).[13]

Many studies conducted at APL to understand the sensitivity of quartz oscillators[9–12] to low-Earth orbit radiation confirmed that sensitivity relates directly to the physical characteristics of the quartz resonators. APL's designs are evidence of the Laboratory's know-how and "show-how" in radiation-hard quartz crystal oscillator technology.

THE STAGE IS SET FOR TECHNOLOGY TRANSFER

Although Syntonics received an exclusive license[14] to manufacture APL's oscillator technology in 1999, the process really began in 1980 with the passage of the Bayh-Dole Act (see the article by Gray, this issue), which grants universities the right to retain title to inventions made under federally funded research. In turn, the government obligates the university to transfer the technology into the commercial market. The goal of the act is to commercialize technologies funded by taxpayer dollars so as to help spur economic development and promote far-reaching industry-sponsored R&D programs.

Changes in the economic and political climate during the late 1980s and 1990s helped create further incentives for technology transfer. The broad penetration of electronics into consumer products and business systems made civil markets for technology more economically significant than defense work, causing the leadership role in technological innovation to shift substantially from military requirements to civilian drivers. The pace of technological change and the reduction of costs for technology products made the military acquisition system increasingly ineffective. Acquisition reform[15] was initiated to recognize these changes and give industry greater freedom and responsibility for R&D to meet defense and space systems requirements using civilian resources such as off-the-shelf products and production methods.

The combination of Bayh-Dole Act and acquisition reform proved to be a significant catalyst for the Laboratory. By creating a stand-alone company— Syntonics— the standard but highly sophisticated oscillators developed at APL under federal funding are now available to commercial industry, making it easier and more cost-effective for the government to procure them as off-the-shelf items. One-of-a-kind oscillators that require advanced R&D will still be provided by APL. Also, with its ability to manufacture the oscillators using commercial methods, Syntonics is making this unique technology available to a wider range of customers at competitive prices.

THE SYNTONICS MODEL

Although the APL USOs are now available as a commercial product, the market remains limited to companies developing very high-end spacecraft systems and manufacturers of geosynchronous satellites for communications, which typically must operate continuously for at least 15 years. The APL oscillators, with their track record for high reliability, are extremely critical on this type of platform since an oscillator failure results in mission failure.

The Laboratory sought to create a mechanism for the commercialization of USOs that would recognize the limitations on APL as a University Affiliated Research Center (i.e., no production work, avoidance of conflict of interest in relationships with industry), but that would also allow for an appropriate degree of interaction with industry. Expertise to design a viable plan was provided by APL's sister organization, the Office of Technology Licensing in the Johns Hopkins School of Medicine, which creates an average of seven to eight commercial companies a year.

One of the first steps was to identify a leader for the new company. The Laboratory selected entrepreneur and business consultant Bruce Montgomery as the Chief Executive Officer, who would be in charge of all aspects of Syntonics, working independently of APL. In addition to giving the University a minority stake in the company, APL and Syntonics agreed that the Laboratory would concentrate on oscillator R&D

while Syntonics would focus on engineering, production, sales, and marketing.

GROWTH

Since its founding, Syntonics has achieved a number of major milestones. One of the most significant is the \$0.9 million NASA Cross Enterprise Award granted to the company (teamed with APL) in November 2000. This award was based on a NASA Research Announcement for "A Micro-Ultrastable Oscillator for Micro/Nano Spacecraft." Syntonics teamed with APL in response to the announcement. NASA received more than 1600 proposals covering a large range of technology development ideas (only about 7% of bidders were successful).

The APL/Syntonics team proposed to develop a prototype state-of-the-art micro-USO that provides spectral purity and frequency stability approaching today's USOs, but with a mass as low as 50 g and volume as small as 60 cm^3. The current state-of-the-art is a Laboratory prototype oscillator developed for the Pluto-Kuiper mission, with a mass of 320 g and volume of 350 cm^3. By 2003, Syntonics should be delivering performance in a package that is a fraction of the mass of competitive products, a major competitive advantage in space components.

Being selected for the prestigious NASA Cross Enterprise Award means that the company is well on its way to meeting its goals. Between this space-based technology contract and self-funded product development, Syntonics will be spending more than \$1 million over the next 2 years to develop the radically smaller (volume, weight, and power) state-of-the-art USO. This should directly benefit the products that Syntonics will market to the satellite industry.

Syntonics's biggest challenge is managing company growth, including staff, facilities, and financing. Syntonics was one of the first tenants in the Howard County Economic Development Authority's NeoTech Incubator. As such, Syntonics has access to a wide array of business services and resources that are available and shared with NeoTech's other high-tech incubator companies. Being a highly specialized company addressing a very limited market, it is not attractive to venture investors. For the foreseeable future, Syntonics will grow by reinvesting the profits from its contracts, using the money to hire new employees, purchase new equipment, and so on.

By the end of 2001, Syntonics will have signed two production contracts as well as finalized the details of the NASA research award. Sales for 2001 are expected to approach \$2 million. The company has now begun a period of steady growth. Further, APL, which retains the right to conduct oscillator R&D and produce one-of-a-kind products, will receive additional R&D work as a result of the Syntonics licensing agreement, including a research contract from Syntonics.

BUSINESS APPLICATIONS

The market for spacecraft precision oscillators is segmented by technical performance (principally frequency stability and phase noise) into three tiers. Within each performance tier, vendors compete on technical specifications, including mass, power consumption, and price. The tiers, from most to least complex, are as follows.

USOs are custom or semi-custom devices, typically procured in small quantities. They provide signals with excellent short-term frequency stability (Allan variance; see Table 1), typically better than 5×10^{-13} over a 1-s period. Their phase noise performance is usually not as critical as their short-term frequency stability. USOs are highly attractive in many applications when compared with alternative, more expensive rubidium or cesium technologies (Table 1).

Master oscillators (MXOs) are quartz-based devices used to discipline the low-precision oscillators in each transponder of a communications payload. They

Table 1. Comparison of USOs and other frequency standard technologies (simplified).

Characteristic	USOs	Rubidium- or cesium-based atomic frequency standards
Short-term stability	Best available up to 1000 s (Allan variance[a] down to 4×10^{-14} at 10 s)	Allan variance ≈ 10^{-12} (improves to 10^{-13} over 1000 s)
Phase noise	Good (−137 dBc/Hz at 1 Hz)	Poor (phase noise performance degraded by high thermal noise floor)
Radiation susceptibility	Can operate in "worst-case" orbits ($< 1 \times 10^{-11}$ per rad silicon)	Comparable performance possible but expensive. In theory, rubidium systems are less susceptible to radiation effects.
Mass, power	Best available	Rubidium systems require a high-power lamp; cesium systems require a high-voltage power supply.
Reliability	Best available (20+ years demonstrated)	Intrinsic wear-out mechanisms limit life, especially for cesium, although a theoretical life of 15 years is claimed for current rubidium clocks.

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[a] See Table 2 footnote.

typically provide 10-MHz signals with low phase noise and frequency drift rates of 10^{-10} per day. The MXO's phase noise performance is usually more important than its short-term frequency stability. In some models, frequency corrections can be commanded from a ground station.

Precision ovenized oscillators (PXOs) are small devices used in RF and digital applications. Frequencies range from 10 to 140 MHz, with total end-of-life drift of 10^{-5} to 10^{-6} per day and no ability to command corrections from a ground station.

Leveraging its APL heritage, Syntonics is positioning itself as a specialty supplier of high-performance time and frequency electronics. Table 2 summarizes Syntonics's major product line for space-qualified oscillators based on the APL-transferred technology. The company

Table 2. Oscillators based on APL transferred technology available to commercial customers from Syntonics.

	USB1010 COSMIC Beacons	USO2010 Planet-B Oscillator	USO2020 Mars Observer	USO2021 Cassini Oscillator
Output (MHz)	1 × 150.012 1 × 400.032 1 × 1066.752	1 × 19.11574	1 × 19.143519	1 × 114.966
Output frequency setting accuracy	2.0×10^{-6}	8.0×10^{-8}	4.7×10^{-7}	4.7×10^{-7}
Aging rate/24 h[a]	1.4×10^{-8}	1.0×10^{-11}	$<6.0 \times 10^{-11}$	1.7×10^{-11}
Allan variance[b] at measurement intervals of				
0.1 s		n.m.[c]	2.0×10^{-12}	n.m.
1 s		4.10×10^{-13}	2.0×10^{-13}	1.5×10^{-13}
10 s		2.06×10^{-13}	$<4.0 \times 10^{-13}$	1.0×10^{-13}
100 s		1.31×10^{-13}	$<3.0 \times 10^{-13}$	7.0×10^{-14}
1000 s		2.65×10^{-13}	$<3.5 \times 10^{-13}$	8.0×10^{-14}
Phase noise (SSB[d]) for frequency offsets of				
0.1 Hz		n.m.	n.m.	n.m.
1 Hz		−116 dBc/Hz	−108 dBc/Hz	−98.6 dBc/Hz
10 Hz		−130 dBc/Hz	−125 dBc/Hz	−117.4 dBc/Hz
100 Hz		−140 dBc/Hz	−131 dBc/Hz	−123.4 dBc/Hz
1000 Hz		−142 dBc/Hz	−131 dBc/Hz	−125.8 dBc/Hz
10,000 Hz		−142 dBc/Hz	−131 dBc/Hz	−125.7 dBc/Hz
100,000 Hz			−131 dBc/Hz	
Frequency as a function of				
Temperature (°C), typically from 20° to 40°C	1.0×10^{-7}	7.0×10^{-13}	8.5×10^{-12}	1.7×10^{-12}
Load, typically 50 Ω ±10%				
Input voltage		5.0×10^{-13}		
Radiation				
Magnetic susceptibility (per Gauss)			8.9×10^{-11}/G	8.7×10^{-13}/G
Acceleration			$3.9 \times 10^{-9}/2\,g$ (worst-case axis)	
Launch vibration	Passed*	Passed*	Passed*	Passed*
Output characteristics				
Power level	0 dBm	0 +1.1, −0.1 dBm	0 +0.33, −0.15 dBm	0 +0.7, −0.3 dBm
Harmonics of f_0 (dBc)[h]	<−30	−54	−58	−56
Spurious (dBc)	<−30	−78	None <100 dBc in 3 MHz bandwith	−70
Physical characteristics				
Power at 25°C (W)	<1 (oscillator)	0.5	2.2	2.2
Max. turn-on power (W)	n.m.	0.78	4.2	4.2
Mass	<750 g	460 g	1300 g	1300 g
Size	14.4 × 9.8 × 6.0 cm	12 × 10 × 5.79 cm	16.8 × 10.2 × 10.2 cm	16.8 × 10.2 × 10.2 cm
Comments	Switchable oscillators; multiple, coherent, amplified RF outputs, some modulated		Includes oscillator, frequency synthesizer, and power conditioning	Includes oscillator, frequency synthesizer, and power conditioning; designed for mission to Saturn

[a]Aging rate = the frequency shift ($\Delta f/f$) of a precision frequency source observed or normalized over a 24-h period in Hz/Hz; [b]Allan variance (also known as two-sample variance) = a measure of the frequency stability of a precision frequency source in the time domain in Hz/Hz; [c]n.m. = not measured; [d]SSB (single side band) phase noise = a measure of the spectral purity of a precision frequency source in the frequency domain typically normalized to a 1-Hz bandwidth and measured at

is initially focused on products built around quartz USOs that are used in space for

- High-performance communications. All communications satellites use oscillators to discipline the operating frequencies of the transponders that are receiving and transmitting radio waves. Demanding communications applications can require a USO. The trend to increasingly higher frequencies (e.g., K_a, K_u bands) is driving a requirement for increasingly stable, low phase noise frequency reference sources.
- RF science experiments. Instruments to accomplish RF sounding of planetary atmospheres are used on some of NASA's deep space and Earth observation research satellites.
- Precision navigation applications. Some navigation techniques require very accurate timing to calculate

Table 2. (continued)

	USO2030 Pluto Oscillator	USO2040 GRACE Oscillator	USO2050 Millitary Oscillator	USO2060 TOPEX FRU
Output (MHz)	1 × 19.11574	1 × 38.656000 1 × 38.656792 1 × 57.984000 1 × 57.985188	8 × 10 6 × 20 2 × 400	8 × 4.096 10 × 5 4 × 19.056392
Output frequency setting accuracy	8.0×10^{-8}	5.0×10^{-8}	2.5×10^{-8}	1.0×10^{-8}
Aging rate/24 h[a]	2.0×10^{-11}	5.0×10^{-10}	3.0×10^{-10}	3.0×10^{-11}
Allan variance[b] at measurement intervals of				
0.1 s	1.0×10^{-12}	4.0×10^{-12} (0.2 s)	1.0×10^{-11}	$<1.0 \times 10^{-12}$
1 s	3.0×10^{-13}	2.0×10^{-13} (2 s)	2.0×10^{-12}	$<2.5 \times 10^{-13}$
10 s	1.0×10^{-13}	2.0×10^{-13}	5.0×10^{-13}	$<7.0 \times 10^{-14}$
100 s	1.0×10^{-13}	3.0×10^{-13}	5.0×10^{-13}	$<1.0 \times 10^{-13}$
1000 s	2.0×10^{-13}	5.0×10^{-13}	n.m.	$<1.0 \times 10^{-13}$
				(5 MHz outputs)
Phase noise (SSB[d]) for frequency offsets of				
0.1 Hz		−95 dBc/Hz, integrated 0.1 Hz to 100 kHz	n.m.	n.m.
1 Hz	−120 dBc/Hz		−110 dBc/Hz	<−128 dBc/Hz
10 Hz	−135 dBc/Hz		−135 dBc/Hz	<−140 dBc/Hz
100 Hz	−145 dBc/Hz		−145 dBc/Hz	<−148 dBc/Hz
1000 Hz	−150 dBc/Hz		−150 dBc/Hz	<−153 dBc/Hz
10,000 Hz	−150 dBc/Hz		−150 dBc/Hz	<−153 dBc/Hz
100,000 Hz			−150 dBc/Hz	(5 MHz outputs)
Frequency as a function of				
Temperature (°C), typically from 20° to 40°C	1.0×10^{-12}	1.0×10^{-12}	2.0×10^{-12}	1.0×10^{-14}
Load, typically 50 Ω ±10%	2.0×10^{-12}		1.0×10^{-11}	*[e]
Input voltage	1.0×10^{-12}		1.0×10^{-11}	*
Radiation	1.0×10^{-10}/rad	1.0×10^{-11}/SAA[f] pass (unshielded)		*
Magnetic susceptibility	2.0×10^{-12}/G	1.0×10^{-13}/G	2.0×10^{-12}/G	*
Acceleration	$1.5 \times 10^{-9}/g$		$2.0 \times 10^{-9}/g$	*
Launch vibration	Passed*	Passed*	Passed*	Passed*
Output characteristics				
Power level	0 dBm	0 dBm ± 1 dB	1.5 ± 0.3 V^{pp} across[g] 50 Ω	0 +0.4, −0 dBm (5 MHz outputs)
Harmonics of f_0 (dBc)[h]	−50	−40	−50	<−58 (5 MHz outputs)
Spurious (dBc)	−60	−60	−65	−95 (5 MHz outputs)
Physical characteristics				
Power at 25°C (W)	0.8	2.8	*	14
Max. turn-on power (W)	n.m.	n.m.		n.m
Mass	320 g (est.)	2.2 kg	*	9.975 kg
Size	9.65 × 6.86 × 5.33 cm	*	*	34,013 cm^3
Comments	Lightweight USO with magnesium housing	Output port-to-port isolation of better than 60 dB	16 outputs at 3 frequencies; port-to-port isolation better than 55 dB	11 redundant outputs (22 total) at 3 frequencies; port-to-port isolation better than 60

discrete Fourier frequencies from the carrier in dBc/Hz[16,17]; [e](asterisk) detailed specifications available from Syntonics LLC at www.syntonicscorp.com; [f]SAA = South Atlantic Anomaly; [g]peak-to-peak voltage, V^{pp}; [h]fundamental frequency f_0 of the USO.

the location of a spacecraft. Other new applications—such as large aperture antennas formed by antenna elements flying in formation on multiple spacecraft—will require very accurate knowledge of the location of those spacecraft relative to each other.

CONCLUSIONS

The Johns Hopkins University approach to establishing a new start-up commercial company (Syntonics LLC) demonstrates an effective and practical method of transferring APL-developed technology into the public domain. Thanks to a wealth of University experience regarding this type of venture, a proven business model as well as excellent in-house counsel ensured the high level of success. Despite initial internal and external concerns regarding APL's first-ever foray into creating a commercial company, industry and sponsor feedback has been overwhelmingly positive as underscored by the recent NASA research award and the two production contracts. By creating Syntonics, APL-developed USOs are available outside the government for the first time. The commercial industry may buy them for their own use or purchase them to use on government contracts, thus lowering costs and removing a layer from the federal acquisition process.

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