Q-TECH Corporation WHITE PAPER

New Space Applications Add to Mix of Space-Qualified Crystal Oscillators

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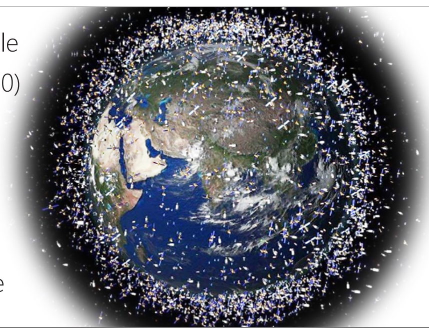
The low-earth orbit (LEO) satellite realm has spawned an entirely new class of devices requiring innovations in crystal oscillator products to meet performance and price benchmarks. Manufacturers of space-qualified crystal oscillators, like Q-Tech, have developed a range of devices (XO, TCXO, VCXO, and others) to provide optimized price and performance for each orbital application. This paper will delve into the subject with the objective of providing an informed understanding of the elements that go into device selection.



It's getting crowded up there. A recent article in the Pittsburgh Post Gazette (May 20, 2020) estimated that there are 2,200 operational satellites orbiting our planet. But that pales in comparison to the anticipated 50,000 or more expected within the next ten years. This explosive growth is being driven by the exponentially expanding demand for satellite navigation, internet and telecommunications mega-constellations. SpaceX's Starlink, Amazon's Kuiper, OneWeb and others are among the companies driving this vast expansion.

From the Space Race to New Space

It all started in the mid-1950s when the U.S.S.R. successfully launched Sputnik. People all over the planet watched in wonder as this bright object made its way across the nighttime sky. And so, the "space race" began with space superiority taking on political-economic implications.

AT&T's Telstar was launched in 1962, spawning its own top-selling instrumental recording. About that same time, President John Kennedy called upon the nation to "commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth."

In its early stages, nearly all U.S. space activity was driven by government space exploration and military programs with some exceptions. The Commercial Space Launch Act of 1984 recognized the private sector regarding launch vehicles, orbital satellites and private launch services.

Early commercial satellites were deployed in geosynchronous (GEO) orbit. A circular geosynchronous (geostationary) orbit has a constant altitude of 35,786 km (22,236 mi). GEO satellites remain in fixed position over the earth allowing antennas to also remain fixed. The GEO orbit height allows communication over a wide area of the earth's surface. An early example of a commercial GEO satellite launched in 1964, Syncom 3, was designed to allow Pan-Pacific coverage of the 1964 Summer Olympics in Japan. Many commercial applications today utilize GEO, particularly systems employing large numbers of fixed receivers (e.g., DirectTV).

Medium-earth orbit (MEO) satellites, which occupy a wide altitude band from 2,000 to 36,000 km above the earth's surface, are not geostationary. MEO satellites are only visible from any receiver from two to eight hours. Telstar is an early example.

The largest growth in the crowded atmosphere will be from the emergence of low-earth orbit (LEO) satellites, orbiting from 160 to 2,000 km above the earth's surface. The low orbit results in smaller footprint for signal reception, averaging 1,000 square kilometers. Satellites in this "new space" orbit move quickly, orbiting the earth every 90 minutes. LEO satellites are much less expensive (per satellite) to launch, use much less power, but need many satellites (clusters) to effect continuous communications with fixed antennas. OneWeb is an early example.

Satellite Applications by Orbit

The range of applications for earth-orbiting satellites is quite extensive. Table 1 provides a general view of the types of satellite applications typically found in each orbit.

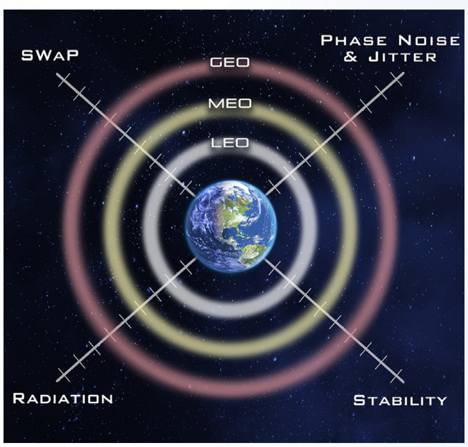
Table 1. Typical Applications for Earth-Orbiting Satellites

Orbit	Applications
LEO:	Communications, Earth Observation, Research, Imagery, Manned Spaceflight (ISS), Military, Space Observation, Spacecraft Repair, Supply Transport (ISS), and Weather
MEO:	Communications, Navigation
GEO:	Communications, Earth Observation, Military, Research, Space Exploration, Space Observation, Weather
Deep Space:	Exploratory Rover, Planned Manned Spaceflight, Planet Exploration, Space Exploration
Launch Vehicles:	Various Programs

Regardless of orbit, all of these applications have in common the requirement for ultra-high reliability electronic components. Quartz crystal oscillators are preferred in many of these over alternative devices for timing and frequency applications. (See the Q-Tech white paper comparing quartz crystal oscillator performance to MEMS devices. Appendix A provides an extensive list of applications, by program name, and the Q-Tech crystal oscillators actively used in each program.)

Performance Requirements Driven by Orbit and/or by Application

All satellites, regardless of orbit, require space-qualified electronic components. Reliability remains an essential component. Hardware is expensive to produce and to launch, so redundancies are built into the design. "Services calls" are not possible, so parts must meet minimum performance and reliability criteria based on application, orbital location and expected mission life.



Crystal oscillator packages are hybrid devices containing the tuned crystal and electronic circuitry. The types of devices can fall into several categories:

XO – Crystal oscillator
TCXO – Temperature-compensated crystal oscillator
VCXO – Voltage-controlled crystal oscillator
MCXO – Microcomputer-compensated crystal oscillator
OCXO – Oven-controlled crystal oscillator
SO – Surface acoustic wave (SAW) oscillator
VCSO – Voltage-controlled SAW oscillator

The remainder of this white paper will provide an overview of the key operational features and performance factors that must be considered in the selection of quartz crystal oscillators based on the application and orbital location, along with the four performance criteria:

- Radiation Hardness
- Stability
- Phase Noise and Jitter
- Size, Weight and Power (SWaP)

Radiation Hardness – TID and SEE

Total Ionizing Dose (TID)

Solar ionizing radiation exposure increases with the altitude of orbit and the resulting reduction on the atmosphere's ability to absorb/reflect its effects. Ionizing radiation does not have an intrinsic effect on a quartz crystal, but as mentioned earlier, quartz crystal oscillators are hybrid devices combining the crystal with semiconductor devices and other components. Semiconductors are susceptible to degradation due to the ionizing effects of solar energetic particle events typically caused by solar flares.

The ability of a device to withstand the operational performance and expected longevity of operation is determined by the device's ability to withstand a lifetime total ionizing dose (TID). TID is measured in kRad. The deeper into space, the higher the TID requirement. Typical ranges for TID are shown in Table 2:

Table 2. TID – Typical Ranges

Orbit	Industry Std	Q-Tech Devices
Deep Space:	100 kRad	up to 300 kRad+
GEO:	100 kRad	100 kRad+
MEO:	100 kRad	up to 100 kRad
LEO:	30 kRad	up to 50 kRad

Single Event Effects (SEE)

In addition to TID, some applications require devices to be tested for performance when subjected to spurious events, like cosmic rays or high-energy protons that can induce device latch-up or other functional interruptions, which are referred to as single event effects (SEEs). SEE testing can be time-consuming and expensive but necessary in many high-reliability applications.

Stability

The stability of an oscillator is driven by two significant factors. The intrinsic stability of the circuit and the effect of temperature on its operation.

Frequency Stability

Stable frequency is of great importance in applications where the oscillator is being utilized in navigation, communications and other precise timing functions. The required degree of stability will be dependent upon both the timing precision and the expected mission life of the system. Generally speaking, frequency stability for crystal oscillators follows the breakdown as described in Table 3 on the following page:

Table 3. Typical Frequency Stability by Oscillator Type

- MCXOs, OCXOs - for "high end" stability (in the ppb, parts per billion range)
- TCXOs – for excellent stability (±1 – ±4ppm, parts per million range)
- Full Space XO, New Space – average is ±50 –±100ppm
  - ±25ppm available in limited temperature ranges
  - Stability changes are much greater than other products, but they are smaller in size and lower in power
- SOs/VCSOs – -200 to +50ppm is the standard stability up to 1.3 GHz

In addition to stability over-temperature performance, aging is important for long life missions, as shown, in order, starting with best:

- OCXOs, MCXOs - ±1.5ppm max over 15+ years
- TCXOs- ±4ppm max over 15+ years
- XOs - ±5ppm max - first year; ±2ppm per year, after

Temperature Stability

Operating temperature variations grow wider as distance from the earth's surface increases. LEO satellites experience a wide range of temperatures (-170 to 123°C) as they encircle the planet and alternate between full exposure to the sun and total darkness. MEO and GEO satellites can experience external temperatures from -250 to 300°C.

All satellites include thermal management to keep the operating temperature within a tighter operating range of only -55°C to +85°C. Most crystal oscillators perform within spec over the full temperature range, but sometimes stability options are chosen depending on a customer's critical/targeted temperatures.

Q-Tech's soon-to-be-space-qualified MCXO offers ppb stability rivaling the performance of its OCXO, but with less size, weight and power (~100 mW vs. multiple Watts for the OCXO). The MCXO uses a dual-mode overtone SC-cut quartz crystal. This self-temperature-sensing resonator virtually eliminates thermometry-related errors yielding temperature compensation five orders of magnitude improvement in temperature-induced change.

Phase Noise and Jitter

Q-Tech offers a full range of oscillators, including XO, TCXO, VCXO, OCXO, MCXO, SO, VCSO, multiple-output LVDS and CMOS clocks, as well as custom configurations and modules where Q-Tech can lock a standard clock to a VCSO to optimize phase noise for near-in and far-out (see plot in Figure 2).

As with stability, phase noise and jitter will vary depending on the device topology.

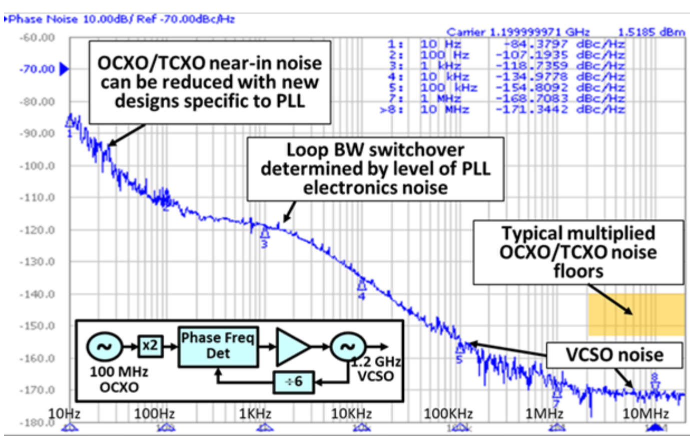


Figure 2: Plot showing Q-Tech oscillators, clocks and modules used for various noise considerations.

In general, the hierarchy of performance is as follows:

MCXOs - Best in Industry

OCXOs - Excellent

TCXOs - Very Good

XOs - Good, but beaten by oscillators above

SAWs - Very good noise floor, but near-in noise is beaten out by other types of oscillators

Size, Weight and Power (SWaP)

Until recently, it could be said that a decreasing SWaP "figure of merit" would apply for satellites deployed in more distant orbits and longer expected lifetimes. But with the advent of "new space" LEO constellations made up of hundreds and possibly thousands of smaller satellites (see Table 4), optimizing SWaP has become nearly a universal objective.

Table 4. Smaller Satellites Used in Popular New Space LEO Constellations

Class	Typical Weight
Small Satellites:	**100 - 500 kg**
Microsatellites:	**10 - 100 kg**
Nanosatellites:	**1 - 10 kg**
Picosatellites:	**0.1 - 1 kg**

Size and Weight

Smaller and lighter devices are often required as designers pack more functions into shrinking payloads. But the size of the package will also depend on other factors, such as stability and temperature. Package sizes typically fall into the following ranges, by type. And weight is directly related to size:

- MCXO: 2" x 1" x .33" tall
- OCXOs: By far the largest (~2" x 2.5" x 1.5" tall)
- TCXOs: Larger than standard XO Hybrids. (1" x 1" x .200" tall)
- Space XOs: Ceramic packages as small as 5mm x 7mm;
  flatpacks as small as 0.374" x 0.500"
- SAWs: .625" x 625" flat pack
- Ultra-Miniature XO (for New space): ceramic SMD as small as 3.2mm x5 mm

Maximum Power (or max current)

As would be expected, devices with temperature compensation or oven-control circuitry will require more power than a basic XO package:

- MCXO: < 100mW
- OCXO: 2.7W at room temperature, 4.8W at -40°C
  - Higher power at lower ambient temperatures due to operation of the oven heater to control the internal temperature of the oscillator
- TCXOs: 55 – 80mA
- Traditional Space XO: 10 – 50mA
- New Space XO: 2.5mA ~ 40mA

Q-Tech Expertise and Portfolio

Q-Tech has been providing “traditional space” offerings since 1986 and series designed for “new space” applications since 2016. The company’s parts are to be found in literally hundreds of programs (see appendix for partial listing).

Why Choose Q-Tech Oscillators?

Q-Tech can meet the most stringent Space requirements:

- 300+ kRad TID for certain oscillator types meeting unique Space requirements including Deep Space missions
- PPB stability in an MCXO up to 50 kRad TID using much less size, weight, and power compared to a similar performing OCXO
- Phase-locking a TCXO/OCXO to a SAW in a module to gain optimal noise floor performance both a near-in lower frequencies as well as far out far-out higher frequencies
- Produce a multiple output LVDS clock in a single package with up to 12 differential paired outputs to drive multiple FPGAs saving board space
- Produce a multiple output CMOS clock in a single package with up to four outputs
- Provide a TCXO ultra-miniature clock for New Space to meet tighter frequency requirements
- Aside from Q-Tech’s traditional full space offerings, a series entitled B+ is available to expand product and screening options to meet end-customer program custom source control requirements
- Service a broad variety of screening specification requirements within the B+ Traditional Space offerings as well as customize even more to a customer’s drawing requirements
- Provide optimal 2-pt mount oscillators in ultra-miniature packages to 18,000 g’s
- Able to manufacture 3 and 4-pt mount oscillators for Traditional Space offerings to 20,000 g’s including a 5 x 7mm 4-pt mount package for Traditional Space
- High-frequency SAW and VCSO oscillators for high-frequency applications achieving up to 1.3+ GHz
- Swept or non-swept quartz are both options.
- Screening options including various deviations of MIL-PRF-55310, MIL-PRF-38534, and EEE-INT-002 with a variety of logic output types.
- Q-Tech has built an extensive radiation library that helps to assist with customer qualifications.

Table 5, below, provides a snapshot of the Q-Tech space-qualified parts series and pertinent details.

Table 5. Q-Tech Devices by Type and Applciation.

Q-TECH CORPORATION

Q-Tech Space Component Differences

	Full Space	B+	QT780 Series (New Space)	QT723 / QT735 (New Space)
Heritage	30+ Years	10+ Years	Since 2016	Since 2019
Export Control	9A515.e.1	EAR99	EAR99	EAR99
Crystal Mount	3 Point round blank	3 Point Mount (Flat Pack, DIP, TO) 4 point mount (Ceramic Pkg)	2 point mount (5x7mm) 4 point mount (7.37x8.89mm, QT778)	2 point mount
Crystal	Swept	Swept or Non-Swept	Non-Swept	Non-Swept
Radiation Hardness	100kRad (300kRad) TID	100kRad TID	50kRad TID	50kRad TID
Standard Screening Options	MIL-PRF-38534, Class K, Modified per Q-Tech 0401-00298-0001	MIL-PRF-38534, Class K (modified) MIL-PRF-55310, Level S MIL-PRF-55310, Level B + PIND EEE-INST-002, Level 1	MIL-PRF-55310, Level B + PIND	MIL-PRF-55310, Level B + PIND
Logic Types	CMOS, LVDS	CMOS, TTL, LVDS, LVPECL	CMOS, LVDS, LVPECL	CMOS, LVDS, LVPECL
Size/Package	0.625" x 0.625" Flat Pack .505" x .808" 14 Pin DIP	Various Flat Pack, Ceramic SMT, Leaded Ceramic, TO, and DIP options as small as 5x7mm	8.89x13.97mm, 7.37x8.89mm or 5x7mm ceramic SMT	4 Pad 2.5 x 3.2mm (QT723) 4 Pad 3.2 x 5.0mm (QT735, CMOS) 6 Pad 3.2 x 5.0mm (QT735, LVDS/LVPECL)

Conclusion

This paper has presented a broad overview of the key performance parameters that must be considered when choosing the optimum quartz crystal oscillator for a space application. Regardless of the orbit and the application, there are numerous degrees of freedom that will complicate the selection process. It is the ultimate goal of engineering design to select the most cost-effective part to meet the physical constraints and performance metrics required in the application.

Ultimately, finding the proper of quartz crystal oscillators for space applications will rely on cooperation between the design engineer and the vendor. Q-Tech has been providing expertise in device selection for longer than any other supplier – over 35 years – and offers more space-qualified parts series than any competitor.

Appendix 1. Quartz Crystal Oscillator Space Applications

Q-TECH CORPORATION

Program	Application	Regime	Part Series	Osillator Type(s)
StaOne D1	Communications	GEO	VARIOUS	VARIOUS
IMMARSAT 6	Communications	GEO	VARIOUS	VARIOUS
VIASAT-2	Communications	GEO	VARIOUS	VARIOUS
Eurostar E3000	Communications	GEO	QT1	XO
INTELSAT VII	Communications	GEO	QT625, QT606, QT31005	XO, OCXO
Globalstar	Communications	LEO	VARIOUS	VARIOUS
AEHF	Communications	GEO	QT625	XO
"702" Platform	Communications	GEO	VARIOUS	VARIOUS
Iridium	Communications	LEO	QT625	XO
AL YAH	Communications	GEO	QT805, QS021	TCXO, XO
ARABSAT	Communications	GEO	QT625, QT606, QT80X	XO, TCXO
HELLASAT	Communications	GEO	QT625, QT606, QT80X	XO, TCXO
ARSAT	Communications	GEO	QT606	XO
STAR3	Communications	GEO	QT822, QT190	TCXO, XO
GEO STAR-2	Communications	GEO	QT822, QT812	TCXO
HYLAS	Communications	GEO	QT82X	TCXO
GEOSTAR-3	Communications	GEO	QT190, QT822	XO
MEXSAT	Communications	GEO	QT31005	OCXO
SB-SAT	Communications	LEO	QT82X	TCXO
REGYS-20	Communications	GEO	QT625	XO
SPECTRUM	Communications	LEO	QT328, QT625, QT128	XO
SPACEBUS 4000	Communications	GEO	QT625	XO
TESLA-C	Communications	LEO	QT625	XO
O3B	Communications	MEO	QT625	XO
TAS Immarsat 7	Communications	GEO	VARIOUS	VARIOUS
ASTRO	Demo Program	LEO	QT1, QT625, QT82	XO
Landsat	Earth Observation	LEO	QT625, QT812, QT192	XO, TCXO, B+ XO
GEDI	Earth Observation	LEO	QT725, QT625, QT812, QT4200	SAW, XO, TCXO, OCXO
ALOS-2	Earth Observation	LEO	QT606, QT625, QT6	XO
AQUILA	Earth Observation	LEO	QT6, QT26, QT188	XO, VCXO
ASNARO	Earth Observation	LEO	QT625, QT824	XO, TCXO
CSO	Earth Observation	LEO	QT6, QT606, QT625, QT641, QT25	XO
ICE-SAT-2	Earth Observation	LEO	QT625	XO
FORMASAT	Earth Observation	LEO	VARIOUS	VARIOUS
GAIA	Earth Observation	Deep Space	QT625	XO
GEOSAT	Earth Observation	GEO	QT106	XO
GOKTURK	Earth Observation	GEO	QT625, QT25	XO
KOMPSAT-3A	Earth Observation	LEO	QT606, QT1, QT78	XO
PRISMA	Earth Observation	LEO	QT625	XO
RADASAT	Earth Observation	GEO	VARIOUS	VARIOUS
SAOCOM-1	Earth Observation	LEO	QT606	XO
INGENIO	Earth Observation	LEO	QT625	XO
WORLD VIEW 3	Earth Observation	LEO	QT188	XO
Proba-V	Earth Observation	LEO	QT625	XO
JPSS-1	Earth Observation	LEO	QT801, QT78	TCXO, XO
JPSS-2	Earth Observation	LEO	QT625, QT25, QT812, QS192, QT128	XO, TCXO
PACE MUSTANG	Earth Observation	LEO	QT625, QT194	XO
Sentinel	Earth Observation (sea/land topography & temperature)	LEO	QT625, QT600	XO, TCXO
LANDSAT 9	Earth Observation (sea/land topography & temperature)	LEO	QT625, QT192, QT81X	XO, TCXO, B+ XO
International Space Station	Earth Observation and Research	LEO	VARIOUS	VARIOUS
FALCON	Earth Observation and Research	LEO	QT28, QT93, QT78, QT88	XO
Hyperspectral	Earth Observations	LEO	QT625, QT606	XO
MARS 2020	Exploratory Rover	Deep Space	QT625	XO
KESTRAL	Imagery	LEO	QT625, QT183	XO, B+ XO
ARGOS	Imagery	LEO	VARIOUS	VARIOUS
TROPOMI	Imagery	LEO	QT122	XO

Appendix 1. Quartz Crystal Oscillator Space Applications

Program	Application	Regime	Part Series	Osillator Type(s)
SLS	Launch Vehicle	N/A	QT625	XO
VEGA	Launch Vehicle	N/A	QT606	XO
YENISEI	Launch Vehicle	N/A	QT625	XO
ORION	Manned Spaceflight	Deep Space	QT190, QT188, QT725, QT625, QT90, QT88, QT25, QS188	XO
APOLLO	Manned Spaceflight	Deep Space	QT821	TCXO
CST 100	Manned Spaceflight	LEO	QT190	XO
Next Gen OPIR	Military	GEO	QT193, QT625	XO
X-BAND Satellite	Military	Various	QT625	XO
KESTRAL	Military	LEO	QT183, QT184, QT180	XO
SKYNET 5D	Military	GEO	QT50	XO
Trident D5	Military (missile)	LEO	QT625, QT24	XO
SBIRS	Miltary	GEO	QT625, QT125	XO
GPS Block III	Navigation	MEO	QT625, QT82X, QTV7X, QT625, QT727	XO, TCXO, VCXO, VCSO
ExoMars Rover	Planet Exploration	Deep Space	QT625	XO
MARS Pathfinder	Planet Exploration	Deep Space	VARIOUS	VARIOUS
MARS Observer	Planet Exploration	Deep Space	VARIOUS	VARIOUS
MARS Observer Camera	Planet Exploration	Deep Space	VARIOUS	VARIOUS
Mars Rover	Planet Exploration	Deep Space	VARIOUS	VARIOUS
JUICE	Planet Observation	Deep Space	QT625, QT25, QT82, QT188, QT190, QT122	XO, B+ XO
Galileo	Planet Observation	Deep Space	QT625	XO
Star Tracker	Positioning	Star Positions	QT606, QT625	XO
SARah	Radar	LEO	QT25	XO
PACE	Research	LEO	QT625	XO
EarthCARE	Research	GEO	QT625	XO
PRISMA	Research	LEO	QT625	XO
NAS15-10000	Research	LEO	QT80X	TCXO
SpaceX DRACO	Rocket Engine	N/A	QT625, QT193	XO
HAYABUSA-2	Space Exploration	Deep Space	QT625	XO
PSYCHE	Space Exploration	Deep Space	QT625	XO
LUCY	Space Exploration	Deep Space	QT625, QT192	XO
LUNAR	Space Exploration	Deep Space	QT193	XO
OSIRIS	Space Exploration	Deep Space	QT606	XO
Space Hydra	Space Exploration	GEO	QT641	XO
BEPI COLOMBO	Space Exploration	Deep Space	QT625	XO
JUPITER 2	Space Exploration	Deep Space	QT606	XO
MAVEN	Space Exploration	Deep Space	QT625	XO
Orbital TESS Ka	Space Exploration	HEO	VARIOUS	VARIOUS
Gamma Ray Observatory	Space Observation	Deep Space	VARIOUS	VARIOUS
NSTAR	Space Observation	Deep Space	VARIOUS	VARIOUS
APEX	Space Observation	GEO	QT188	XO
EUCLID	Space Observation	Deep Space	QT625	XO
JWST	Space Observation	GEO	QT625	XO
SPRINT-A	Space Observation	LEO	QT625	XO
SOLAR ORBITER	Space Observation	Deep Space	QT625, QT600, QT28, QT88, QT388, QT92, QT192	XO
ReStore	Spacecraft Repair	LEO	QT193, QT194	XO
CYGNUS	Supply Transport	LEO	QT821	TCXO
GOES	Weather	GEO	QT625, QT641	XO
VIIRS	Weather	Polar	QT625	XO
GEOKOMSAT	Weather	GEO	VARIOUS	VARIOUS
GOES-R	Weather	GEO	QT606, QT25, QT641, QT625	XO
JPSS	Weather	Polar	QT625, QT50	XO
MetOP	Weather	LEO	QT25, QT625, QT802, QT812	XO, TCXO
ATLID	Weather	Various	QT641	XO
METEOSAT THIRD	Weather	GEO	VARIOUS	VARIOUS
MTG Satellite	Weather	GEO	QT625, QT606, QT600	XO