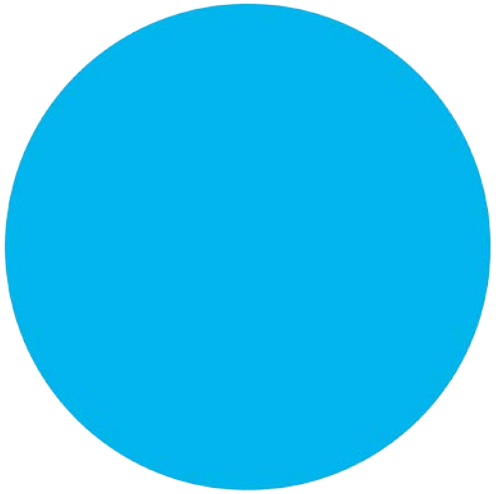

iXblue modulators for space application

Dr Hervé Gouraud – Sales & Marketing Manager iXblue-Photonics

iXblue

TABLE OF CONTENT

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Chapter 1

iXblue in few words

High-Technology Independent Company

600+ employees

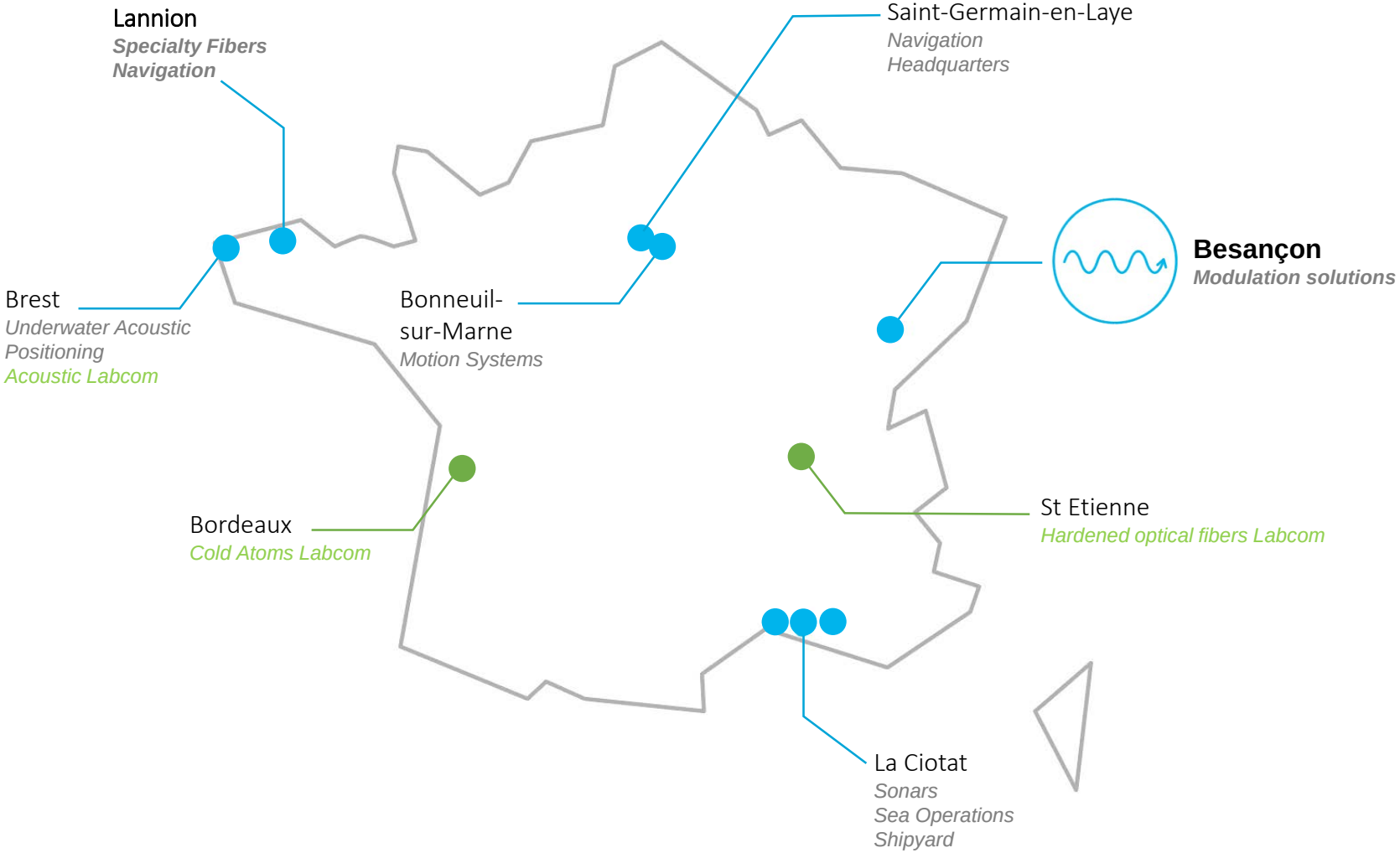
100+ M€ turnover

80% export

30 YEARS' EXPERIENCE
NAVIGATION - POSITIONNING - IMAGING MARKETS

iXblue

iXblue in France



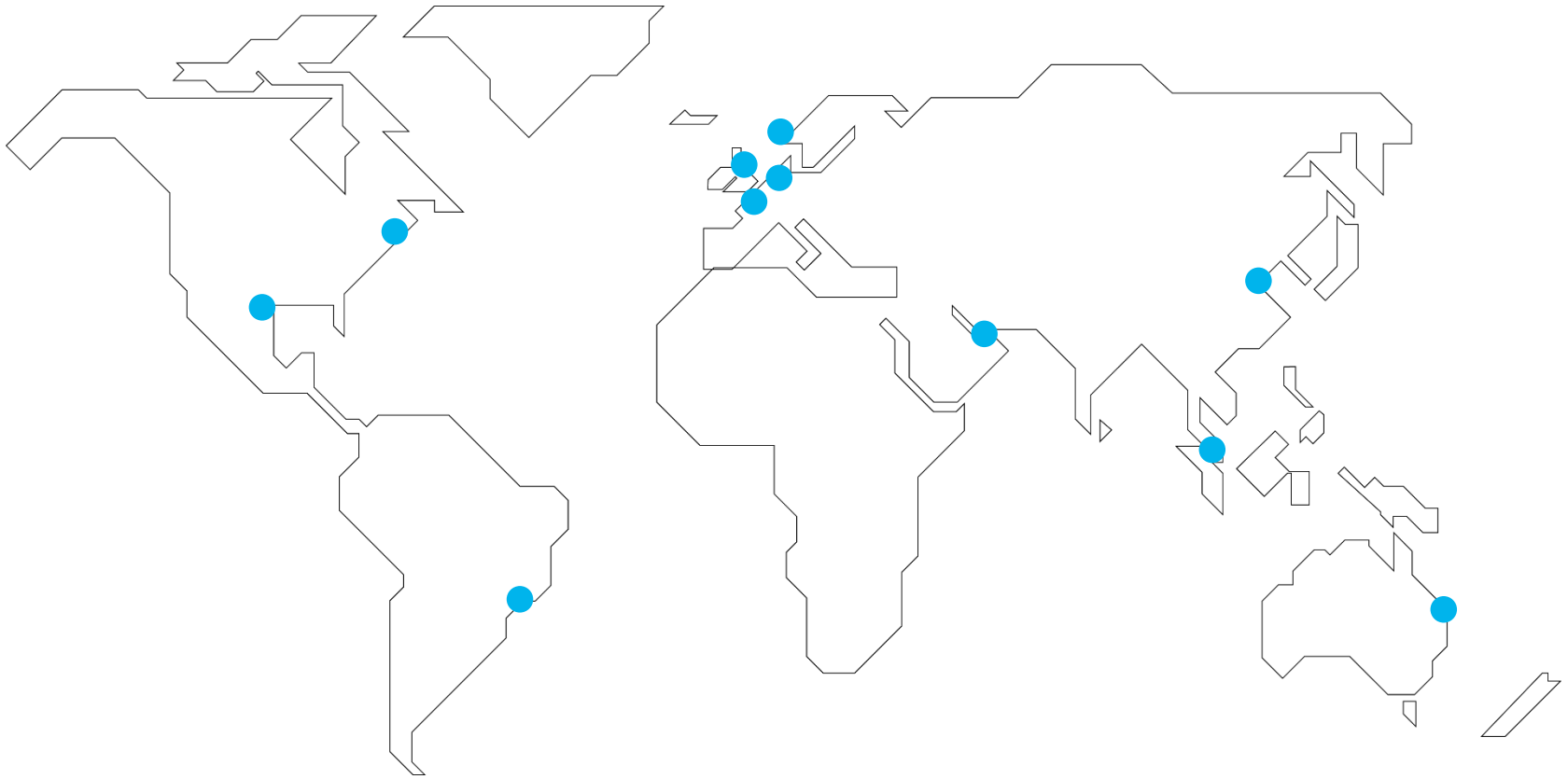
8 industrial sites

100% of R&D and production as well as 90% of suppliers located in France

Joint Research Laboratories

iXblue

Global Footprint



24/7
support

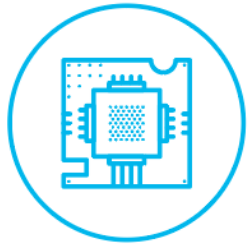
11 offices
Worldwide

iXblue

Products & Services

Specialty fibers
and components

Modulation
solutions



Inertial sensors

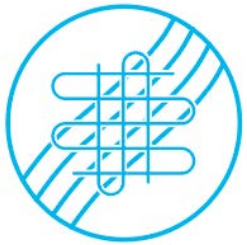
Underwater acoustic
communication
and positioning

Motion simulators
and Pan & Tilt

Navigation systems

Sonars

Shipyard



Sea operations

We offer a wide range of products and services from optical components to instruments, integrated systems and operations at sea.

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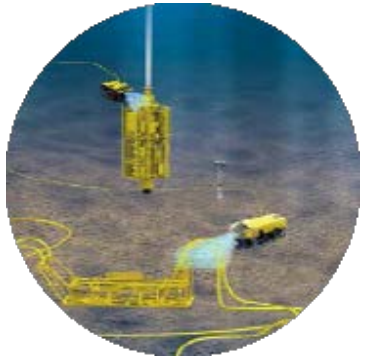
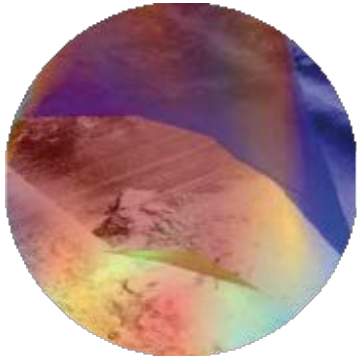
Applications



Energy and Renewables



Hydrography

Space

Defense

Navigation

Autonomous vehicles

Fiber lasers

Fishing and fishery research

Our products are used from the depths of the oceans to outer space in very diverse applications. We encourage strong cross-fertilization, technical and methodological synergies between those applications.

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Chapter 2

What is iXblue Space heritage?!

Modulators from R&D to concrete communication projects

First modulators prototypes developped for space

- **2002 - 2006 Sat'N'Light**
  - In collaboration with Thales Alenia Space,
  - Photonic RF frequency up and down conversion
  - Routing of microwave signals in repeaters

- **2006 - 2014 MGOM**
  - ARTES 5, with Thales Alenia Space, ALTER, University of Madrid
  - Optimized wide bandwidth optical modulator
  - Reliability assessment & evaluation

- **2008 - 2014 OMCU**
  - ARTES 5, with Thales Alenia Space
  - Special linear modulator
  - Packaged modulator for integration in subsystems

ThalesAlenia Space
A Thales / Finmeccanica Company

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Modulators from R&D to concrete communication projects

To the European Space Standard for $LinbO_3$ modulators

- **2010 - 2012**
  - Evaluation of reliability of optical modulators for space conditions
  - Definition of a space qualification program (Flow cart of tests) for optical $LiNbO_3$ modulator

- **2012 - 2013**
  - Study with and for Thales Alenia Space
  - Study of a reflective modulator for array of antenna
  - Optimized optical modulator
  - Reliability assessment & evaluation

- **2013 - 2015**
  - Optimization of hermetic packaging aiming ideal compliance with space requests

esa
European Space Agency

ThalesAlenia Space
A Thales / Finmeccanica Company

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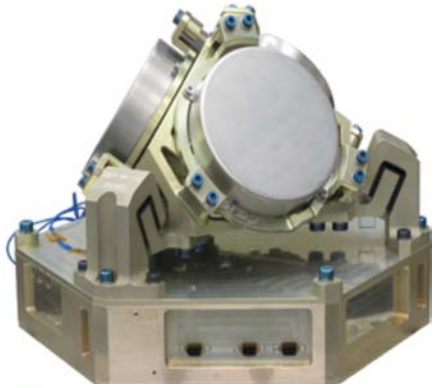
Fiber-Optic Gyroscopes (FOG)

- **Application**
  - iXspace devepped with EADS Astrium a family of ITAR free Inertial Measurements Units, the ASTRIX
  - Navigation, precision positioning

- **Technology:**
  - Each FOG requires 3 Y-Junction Phase modulators and 3 fiber coils
  - $LiNbO_3$ Crystal oriental X-cut
  - APE (Annealed Proton Exchange) process
  - Wavelength: 1550 nm
  - RadHard Fiber coils



iXspace

esa
European Space Agency

cnes

ASTRIUM
AN EADS COMPANY

- **The reality - Commercial projects currently in operation:**
  - PLANCK: May 2009 - Cosmic Background radiation, link
  - PLEIADES: December 2011 - earth observation, link
  - GAIA: December 2013 - three-dimensional map of our Galaxy GALILEO, link
  - Meteosat Third Generation: 2015 - for numerical weather prediction and now-casting, link
  - AEOLUS: August 2018 - Atmospherix Wind profile, link1 link2
  - …

ThalesAlenia
A Thales / Finmeccanica Company Space

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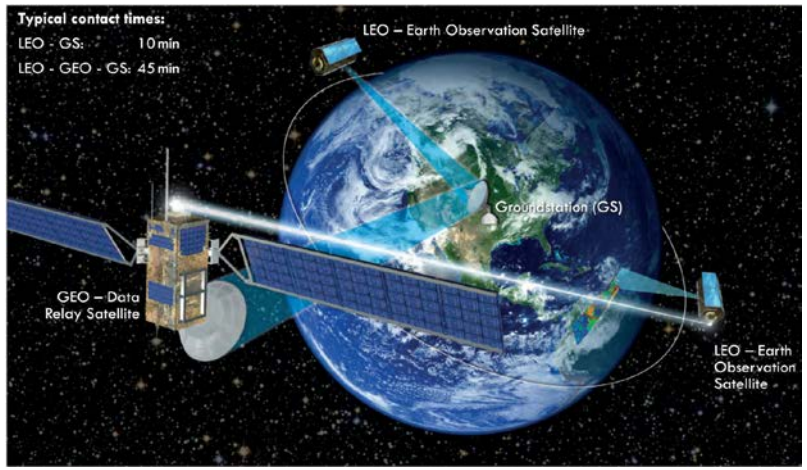
Satellites communications

- **Application**
  - Laser Communication Terminals for LEO-GEO / LEO to LEO / LEO to ground
  - High-speed data transfer

- **Technology:**
  - Amplitude & Phase $LiNbO_3$ modulators
  - $LiNbO_3$ Crystal oriental X-cut
  - APE & Ti:Diffusion processes
  - Wavelength: 1064 nm & 1550 nm
  - Medium frequency < 5 GHz
  - Modulation scheme: BPSK homodyne



- **The reality - Commercial projects currently in operation:**
  - Mission: Sentinal 1a and Sentinel 2a, and on the GEO satellite Alphasat: providing high-resolution optical imagery of agriculture, forests, land-use change and land-cover change, link1, link2

esa
European Space Agency

TESAT SPACECOM
PIONEERING WITH PASSION

NEC

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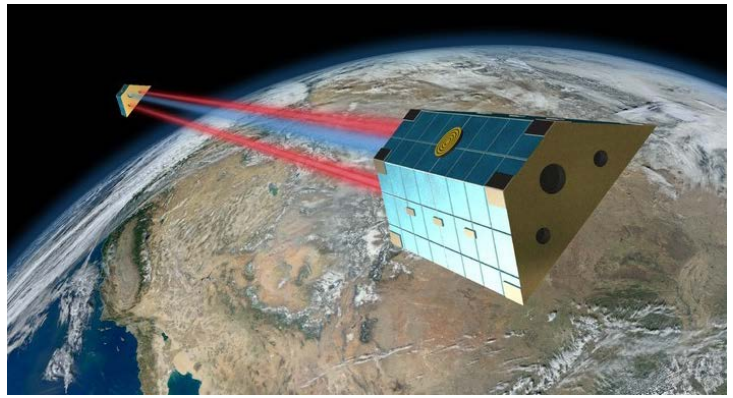
On-board laser cavity stabilization

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

- **Application**
  - Laser cavity stabilization

- **Technology:**
  - Each Laser uses a Phase $LiNbO_3$ modulator
  - $LiNbO_3$ Crystal oriental X-cut
  - APE (Annealed Proton Exchange) process
  - Wavelength: 1064 nm
  - Medium frequency < 100 MHz
  - Pound–Drever–Hall (PDH) technique

- **The reality - Commercial project:**
  - GRACE FO: Gravity Recovery and Climate Experiment Follow-On: tracking Earth's water movement to monitor changes in underground water storage Link1, link2



Twin satellites « Tom et Jerry »

(GRACE-FO) mission launched onboard a SpaceX Falcon 9 rocket, Tuesday, May 22, 2018,

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Laser Communication from Ground to Satellite

- **Application**
  - December 2013 Nasa's first laser communication: Ground ←→ Space: the system is the first ever to use an optical laser rather than radio waves to transmit data across space.

- **Technology:**
  - ModBox "Communication Laser" System Optical transmitter 4 Channels
  - Wavelength: C-Band
  - Modulation scheme: Fourth Order Pulse Modulation (Pulse-Position Modulation PPM-4)

- **The reality - In-situ project:**
  - A communications link between an ESA ground station in Tenerife, the Canary Islands, and NASA's LADEE (Lunar Atmosphere and Dust Environment Explorer) satellite 400 000 km away in orbit round the Moon. Link1, link2

LADEE spacecraft
transmitting to a ground station

National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

European Space Agency

RUAG

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Laser Communication from Ground to Satellite

Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

- **Application**
  - May 10th 2018: Ground Free Space communication: DLR set a new world record in optical free-space data transmission using free-space laser communications – 13 Tb/s

The virtual satellite terminal

- **Technology:**
  - ModBox Optical "Reference Transmitter"
  - Wavelength: C-Band
  - Modulation scheme: 16-QAM - 53 WDM

- **The reality – Lab project:**
  - The distance covered during the trials was 10.45 km and is comparable - with respect to turbulence - to the 'worst-case scenario' connection between a ground station and a geostationary satellite. Link1

The virtual station terminal

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iXblue: the leader in the space communication market

- **iXblue is a world-leading manufacturer of high-reliability $LiNbO_3$ modulators for space market**
- iXblue first study and modulator prototypes for space started in 2002
- iXblue Modulators have been already launched in space through more than **13 missions since 2009 with successful operations**.
- With ESA, iXblue established a Standard / Norm of the $LiNbO_3$ qualification for a space application
- The iXblue **modulators passed successfully all the tests of reliability to be used in space** (radiations, vibrations, mechanical shocks, endurance tests such as thermal cycling and life tests in vacuum,…).
- The iXblue modulators **address the market of space applications** with highly reliable solutions for a wide range of application:
    - Navigation, precision positioning
    - Inter-satellite communication
    - Laser stabilisation
- iXblue masters both Ti:InDifusion / APE processes and provide Space Grade $LiNbO_3$ modulators:
    - Near Infra-Red / C-Band Phase and amplitude modulator
    - MXER: High Extinction Ratio Modulator, ER from 23 dB, to 30 dB in a near future
    - EO-bandwidth from 100 MHz to 40 GHz

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Chapter 3

Why the need of “space grade” $LiNbO_3$ Modulators?

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Space grade Modulators: the environment

Main differences	Standard Telcordia modulators	Space Grade modulators
Operating and storage conditions	**Space environment** could induce additional degradations in a space mission due to: • Rocket launch (vibrations, chocks) • Orbital lifetime (radiations, vacuum, temperature, operating cycles) • Reliability and Lifetime • Lack of accessibility **A Specific Qualification must be performed with specific Radiation doses, vibration and shock amplitude, etc…which are not covered by the Telcordia Qualification.** • Ground storage (temperature, humidity) **The Space Grade modulators are sealed quasi hermetically with neutral and dry gas by seam welding operation.**	
Qualification	The qualification is performed **once and at a given time.** The Qualification is done once for the component life !	**The qualification is usually performed per modulators batch for a given mission** (rocket, satellite type, orbit, life time of the project,…).
Modulator performances	Low $V\pi$, very wide EO-bandwidth	High stringent specifications: • Low $V\pi$, low EO-bandwidth, low insertion loss, • Very low IL & bias drifts **A screening test is required**
Raw materials	**Space environment involves a dedicated raw material choice:** • Already Space qualified elements are used (limitation of neighbors' outgazing and contamination effects) • Glue, fiber-boots, fiber buffer, chip base plate, …. which involve a specific mechanical housing. • Life-time of the elements embedded into the modulators	

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Space grade Modulators: the process

- Space grade modulator: the best modulator quality, due to intensive care during the manufacture!
- 2 engineers follow continuously the modulators manufacture
- Additional control tests are added: visual inspection, pull-test and wirebond testing on samples,
- More than 7 steps are added in the Space modulator manufacturing process applicable from the standard for Space products: ESCC and/or MIL-STD

Main differences	Standard Telcordia modulators	Space Grade modulators
Pre-test on electrical bonding by using a control sample	No	Yes
Post-test on electrical bonding by using a control sample (pull-test)	No	Yes
Seal welding pre-test on a control sample	No	Yes
Seal welding post-test on a control sample	No	Yes
Visual Inspection (Internal elements and/or external)	Yes (~ 3 times)	Yes (~ 5 times)
Number of manufacturing steps from Front End to EOM final test	~ 20	~ 27

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Space grade Modulators: the traceability

- **Traceability** is the ability to verify the manufacture history of the Modulators by means of documented recorded identification.
  - Each wafer is defined by its origin from a bulk lithium niobate crystal and is identified with its own serial number defined chronologically
  - The “Product Line” (GF), define all the fabrication steps of the $LiNbO_3$ wafer, and follows the wafer during the fabrication steps.
  - Each step is defined by a detailed fabrication document, named “Processing methods”.
  - Each step of the GF is checked dated and signed by the operator on the paper document.
  - Each chip on the wafer is identified by a number between 01 to 23 written (in gold) at the surface of the chip during the lithography
  - All characteristics of the chips are stored in an electronic document linked to the wafer type and to its serial number.
  - A document, named “Mounting range” (GM), define all the packaging steps of the $LiNbO_3$ chip, and follows the chip during the fabrication steps.
  - The chip is packaged in a case with its own serial number defined chronologically.
  - All data from specifications of the completed modulator are stored in a document: wafer type and SN, chips serial numbers.
  - Electronic documents are stored on a central storage saving disk system with external saving periodic operations.
  - Paper documents are stored in archives cabinet

- Traceability is especially relevant when developing safety-critical systems such as space grade component

- The traceability plays an important role
  - To act in a curative way to rectify as fast as possible the conformity of the product and\or better manage the consequences/damages caused
  - To realize an analysis of the problem upstream and the downstream to set up corrective actions;
  - To integrate in a preventive way into the design and into the production all the relevant elements;

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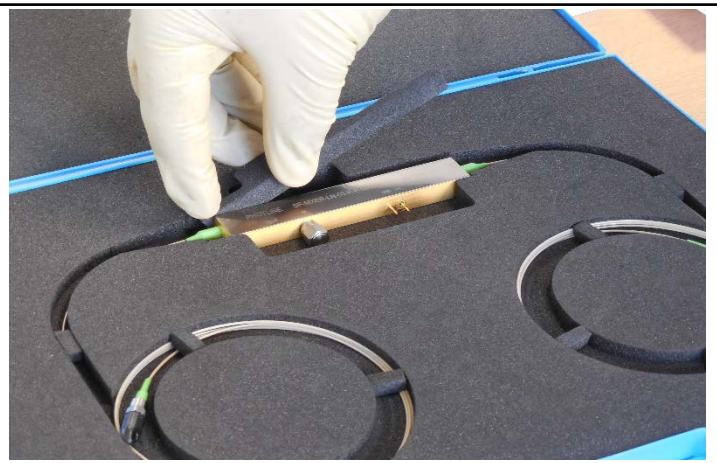
Space grade Modulators: the packaging and delivery

Standard Telcordia modulators	 A carton box is used
Space Grade modulators	 The modulator are conditioned in specific box with dedicated foam arrangement for fiber.  A high protection case is used

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Chapter 4

Which qualification strategy?

The approachs, the notion of risk

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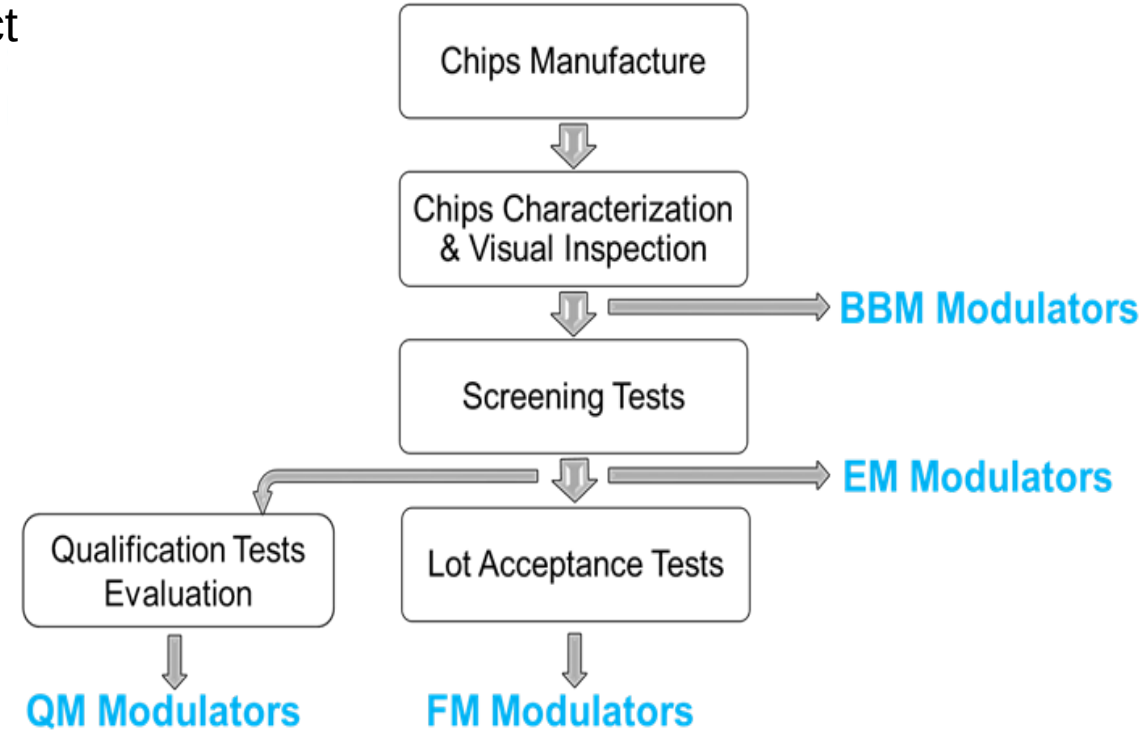
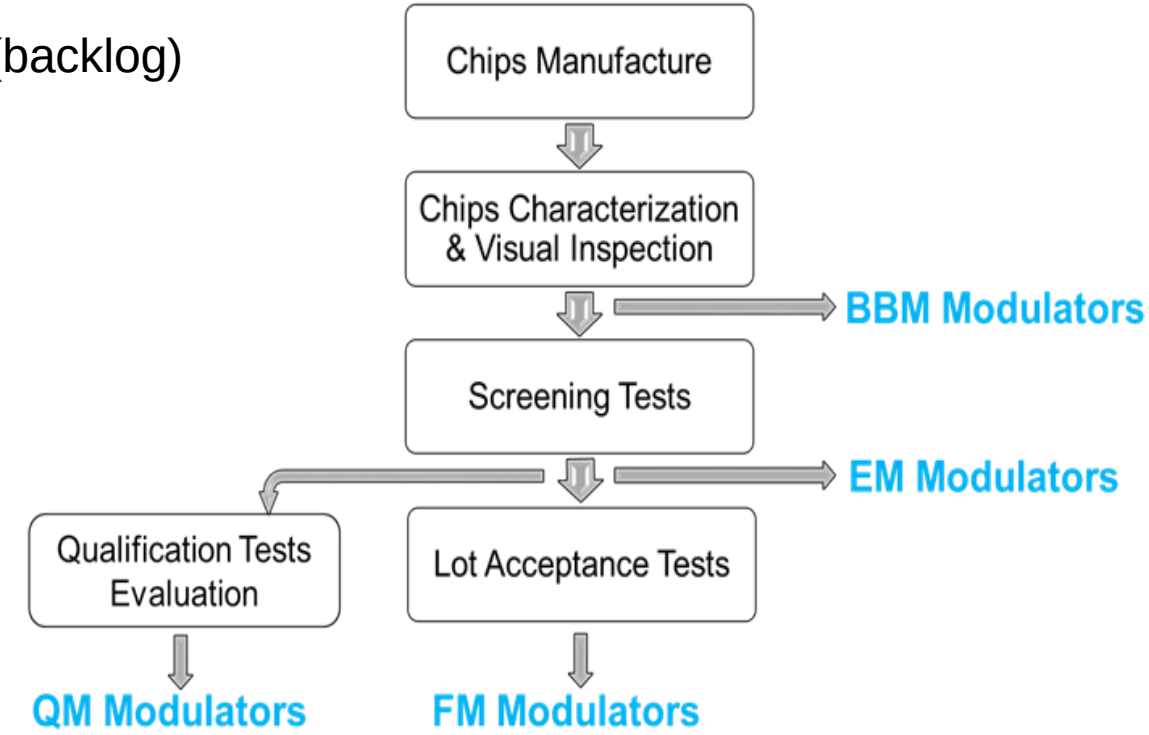
The qualification: the conservative approach

- A full Qualification (Endurance, radiation, mechanical tests chart) is conducted on several QMs.
  - The tests conditions are defined by the mission (rocket type, orbit,…)
  - The QM are tested with an additional margin in comparison with the operating and storage conditions
- The FM are selected from EM batch
- The FMs are submitted to a relaxed tests program (Lot Acceptance Test)
- Dedicated to small volume modulators production project
- Expensive Project / FM delivery is more than 1 year.
- Approach dedicated to long-life satellite, etc…



The qualification: the realistic approach

- Customer takes advantage of iXblue heritage and previous space projects success
- Based on iXblue heritage & background, **the number of QMs can be reduced, and the qualification program is simplified**
- A Delta-qualification is performed only when new process or element are changed
- Dedicated to small up to large volume modulators production project
- Cost effective project / EM-FM delivery is 4 - 8 months (backlog)



Space grade Modulators

- **“New Space” approach**
  - The screening tests is reduced to the burn-in, the qualification on QM program is reduced or not performed,.
  - High master and control of the supplier’s technology and processes
  - Production & standardization dedicated to the small and medium production volume
  - Low-cost or cost effective space solutions
  - Design to cost / process to cost
  - This approach is risky (reliability of the EOM) and can be dedicated only to short life time satellite projects.
  - iXblue does not support this approach today.

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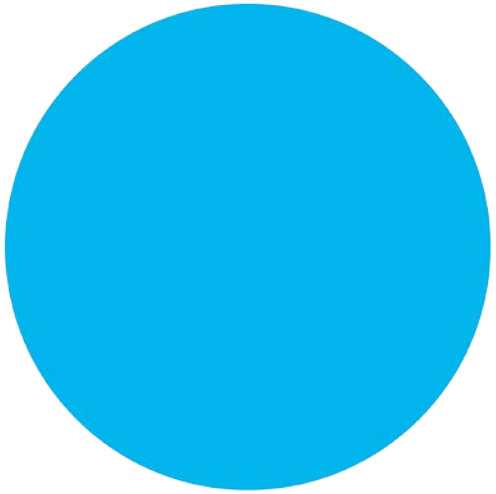

Additional Slides

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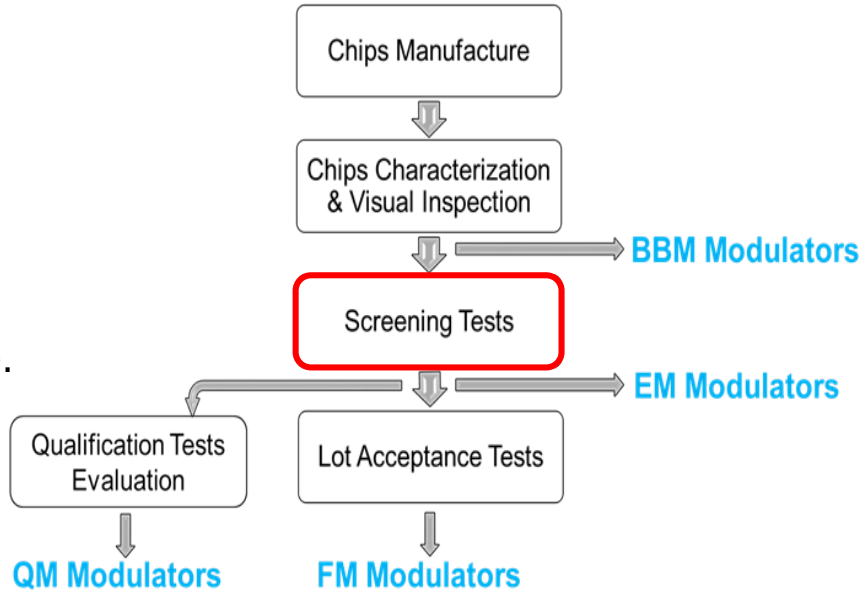
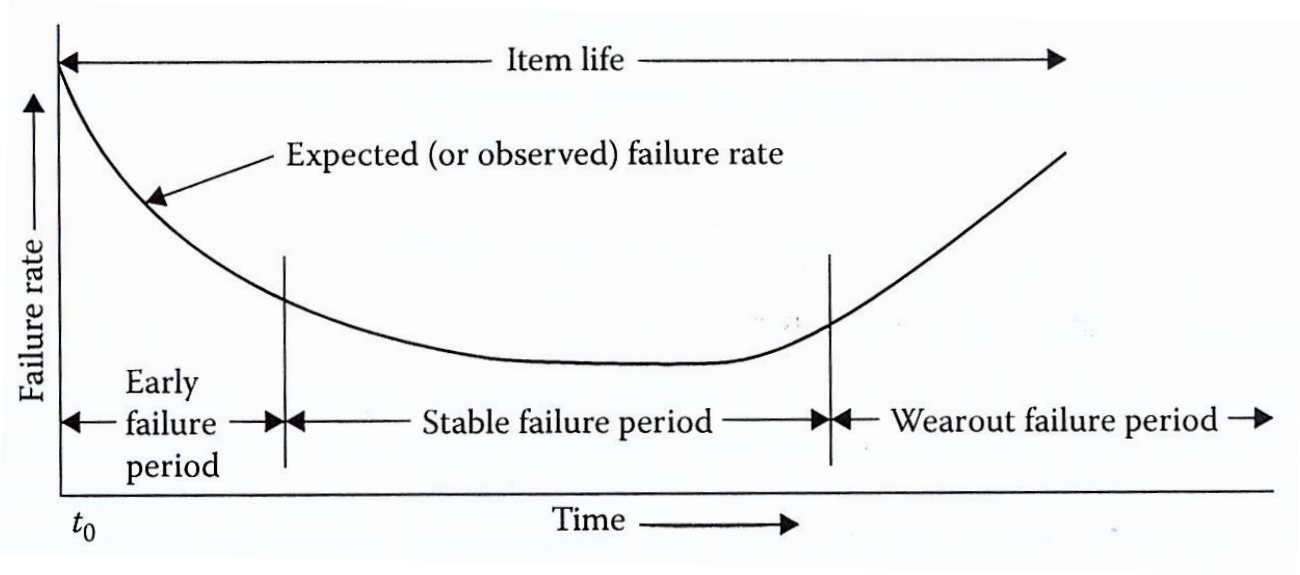
Space grade Modulators definitions

Why the screening test ?



- The Screening aims are:
  - To detect potential failures and defects as early in the test sequence as possible.



- The bathtub curve for failure rates
  - Early failure period or also called infant mortality failures: during this period, the weak or marginally functional modulators are weeded out.
  - Stable failure period or intrinsic failure period: the failures occur in a random at a uniform or constant rate.
  - Wear-out failure period: one of the main purposes of the reliability testing is to ensure that the onset of the wear-out period occurs far enough out in time as to not be concern during the useful life of the product.

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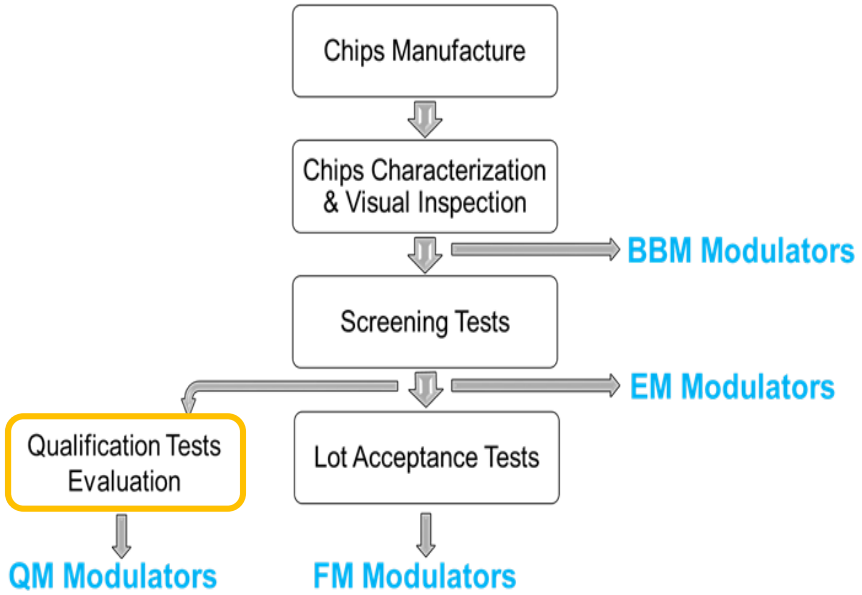
Space grade Modulators definitions

How Important are Qualifications?



- The objective of qualification testing is the formal demonstration that the design implementation and manufacturing methods have resulted in hardware and soft-ware conforming to the specification requirements
- The purpose of qualification testing shall be to demonstrate that the items perform satisfactorily in the intended environments with sufficient margins.
- The qualification test levels shall exceed the maximum predicted levels by a factor of safety which assures that, even with the worst combination of test tolerances, the flight levels shall not exceed the qualification test levels.
- **Radiation Environment**: The space environment could induce degradation to a majority of optoelectronics components employed in a space mission.
- **Damp heat**: The purpose of this test is to evaluate, in accelerated manner, the resistance of the component to the deteriorative effects.
- **Random & Sine Vibration**: Vibration tests verify the ability of the samples to withstand the dynamic stress applied by vibration.
- **Mechanical Shocks**: The purpose of the mechanical shocks test is to examine the modulators shock resistance.
- **Thermal Vacuum & Air cycling**: The modulator being exposed to thermal vacuum during space flight, also the large temperature variations may directly affect the characteristics of the modulator.
- **Accelerated Aging test**: The method consists of simulating long term operation in a relatively short period of time in harmful test conditions. Possibility to anticipate the lifetime of the modulators.

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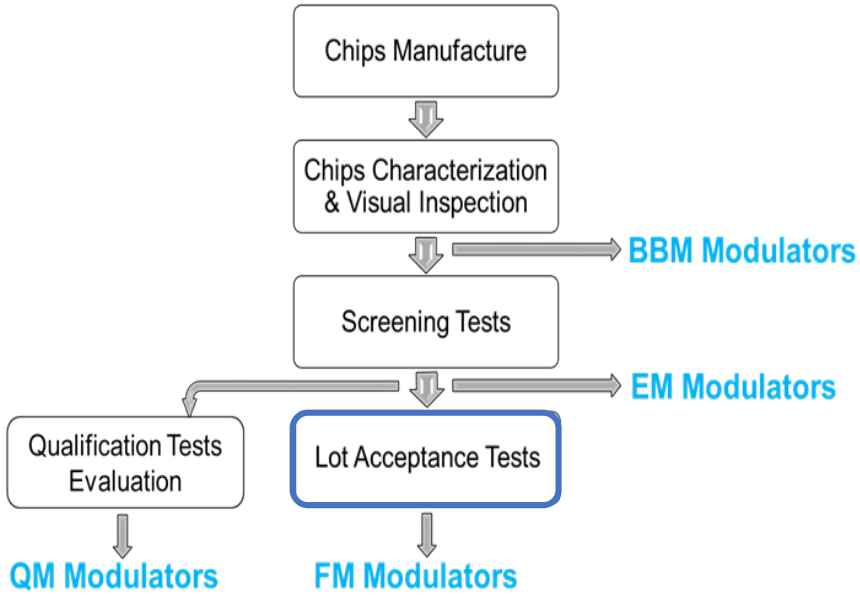
Space grade Modulators definitions

How to get Flight Model Modulators: example of Qualification Test (QT) and LAT



- The purpose of acceptance testing is to demonstrate conformance to specification and to act as quality control screens to detect manufacturing defects, workman-ship errors, the start of failures and other performance anomalies, which are not readily detectable by normal inspection techniques.
- The acceptance tests shall be formal tests conducted to demonstrate the adequacy and readiness of an item for delivery and subsequent usage.
- Acceptance tests shall be conducted on flight models under environmental conditions no more severe than those expected during the mission.

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Space grade Modulators definitions

Models philisophy

- Commercial Off-The-Shelf (COTS),
- Breadboard Model 1 (BBM1);
- Breadboard Model 2 (BBM2);
- Engineering Model (EM);
- Flight Model (FM).

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Space grade Modulators definitions

Models philisophy

The following guidelines are intended to define the $LiNbO_3$ modulator models involved in the verification process and the selection of the associated model.

- The **Commercial-Off-The-Shelf (COTS)** is a commercial and standard $LiNbO_3$ modulator, iXblue portfolio amplitude and phase modulators
- The **Breadboard Model (BBM)** we identify:

  - the BBM1: it can be seen as a COTS modulator model but with a custom $LiNbO_3$ chip (based on customer requirement such as an adapted EO-bandwidth, a lower $V\pi$, a higher SER, a lower IL,…).

  - the BBM2: is identical modulators to flight hardware except for reliability and quality assurance. It is used for the confirmation of key performances (optical, electrical, electro-optical) and behavior, as well as interface and size (mechanical foot-print, fibers,…).

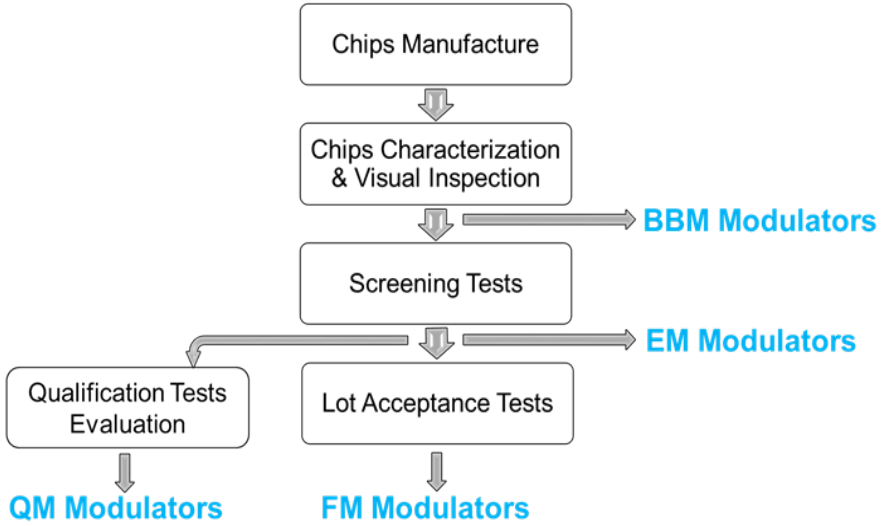
The BBM1 & BBM2 modulators are not intending to be submitted to tests, neither space operating condition.

- The **Qualified Model (QM) and Engineering Model (EM)** are modulators that are used for the confirmation of key performances and interface, including unit mounting scheme and thermal characteristics. These modulators are identical to flight hardware, it is sampled from flight model lot after screening test.

The **QMs** are hardly tested following full level functional and environmental qualification tests (Qualification Tests Evaluation).

Functional qualification is performed on **EM**.

- The **Flight Model (FM)** are the modulators dedicated to fly; these are tested to acceptance-level testing (LAT Lot Acceptance Tests corresponding to a relaxed qualification tests program).



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Space grade Modulators definitions

Differences between COTS, BBM1, BBM2, EM and FM

	-	COTS [1]	BBM1	BBM2 [2]	EM, QM [2]	FM [2]
Raw material	Lithium Niobate Chip	Standard	Standard or customized [3]	Standard or customized [3]	Standard or customized [3]	Standard or customized [3]
	Metal Housing	Standard	Standard	Space-compatible	Space-compatible	Space-compatible
	Electrical & optical connectors (RF & FC)	Standard	Standard	Standard	Space-compatible	Space-compatible
	Fiber jackets	Standard	Standard	Space-compatible	Space-compatible	Space-compatible
	Fiber boots	Standard	Standard	Space-compatible	Space-compatible	Space-compatible
	Embedded elements	Standard	Standard	Space-compatible	Space-compatible	Space-compatible
Assembly Process	-	Standard	Standard	Standard	Space-compatible	Space-compatible
Selection	-	Standard	Standard	Standard	After screening	After screening and LAT

Standard for Space products: ESCC and/or MIL-STD if applicable.

[1] iXblue's standard modulator, see our portofolio on photonics.ixblue.com

[2] Raw material and final modulators coming from the same batch.

[3] Custom $LiNbO_3$ Chip based on non-standard modulator specification.

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Space grade Modulators

How to get Flight Model Modulators: example of Qualification Test (QT) and LAT