ELIXIR Training School

ELECTRICAL and TESTING

Part 1 - ELECTRICAL

Peter Rumler, SRE-PJ

19 May 2011

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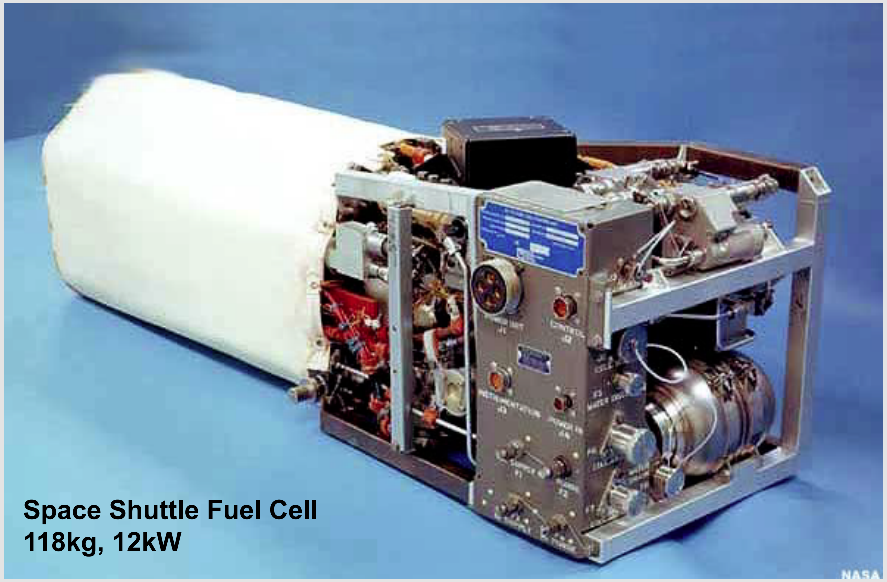
Power and Energy Conversion 1/2

- Like all other machines, a satellite needs a source of energy in order to function.
  As it launches away from Earth it will be running off an onboard battery, but to operate continuously for years on end more long-lived power sources are required such as Solar Arrays, Thermo-nuclear Generators (RTG) or Fuel Cells.

- Power and Energy Conversion covers all aspects of power generation, storage, conditioning and distribution for space applications. The purpose is to optimize solar array, energy storage and distribution designs for particular missions and various orbits, including deep space or very close to the sun.

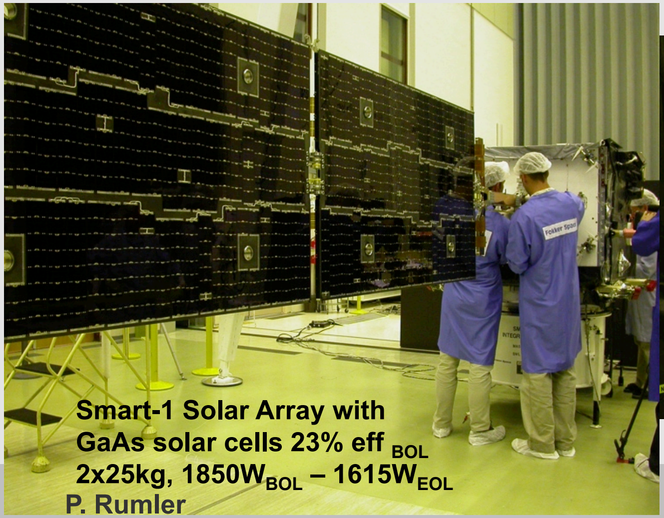
Cassini RTG
65kg, 890W BOL, 630W EOL
7.7kg ^{238}Pu



Space Shuttle Fuel Cell
118kg, 12kW

Power and Energy Conversion 2/2

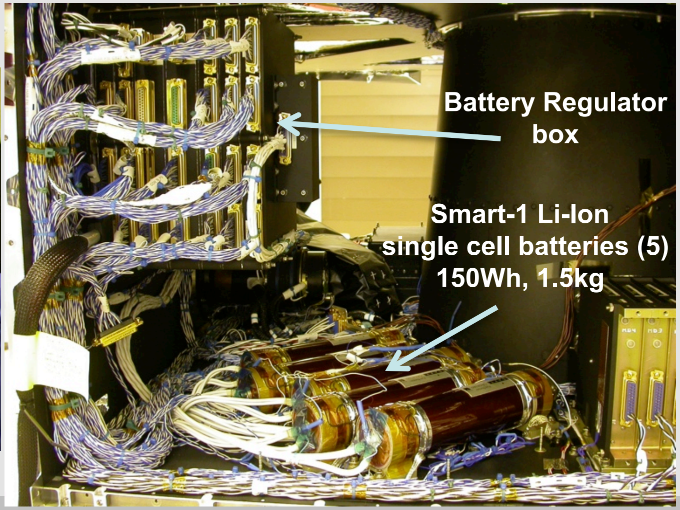
- A reliable, ongoing power supply is essential to a space mission's success. The Sun provides around 1.4 kW/m^2 in low-Earth orbit – and the majority of spacecraft incorporate wing-like solar arrays or else have them layered across their hull. These are composed of linked (in parallel and series) photovoltaic cells which produce an electrical current when light shines on them.
- Photovoltaic cells efficiency remains comparatively low at 28% for the latest designs (GaAs), and their efficiency is further reduced by heating from the Sun and radiation damage during a satellite's lifetime. This means solar arrays have to be built on a large scale to deliver useful power levels, on the order of tens of square meters for a typical communications satellite.
- Most satellites have orbits that will take them out of the Sun into shadow behind the Earth – for a low-Earth orbiting spacecraft that occurs once per orbit – so they are also equipped with rechargeable ('secondary') batteries to keep them powered in the meantime.
- A satellite's electrical loads will generally vary depending on which instruments or subsystems are running at a particular time. So the supply needs to be regulated to ensure they are producing a level of power equal to that required by the satellite. The electricity is then distributed to the various elements requiring it, overseen by the power system.
- The power system also incorporates conditioning and conversion devices to prevent harmful current surges and switch voltages as required – and for reliability is needs to include redundancy and/or majority voting devices (2 of 3)



Smart-1 Solar Array with GaAs solar cells 23% eff $_{BOL}$ 2x25kg, 1850W$_{BOL}$ – 1615W$_{EOL}$

P. Rumler

Solar Array connection test with lamp

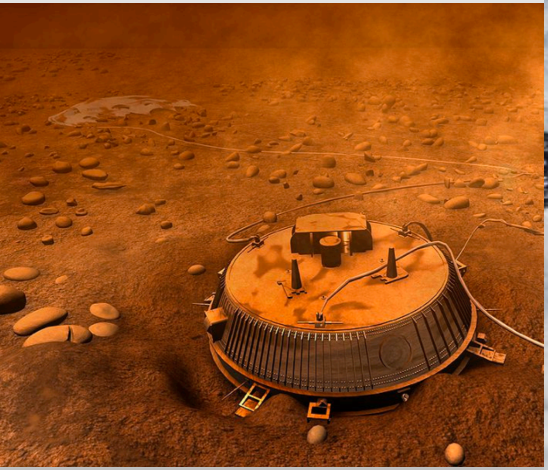


Battery Regulator box

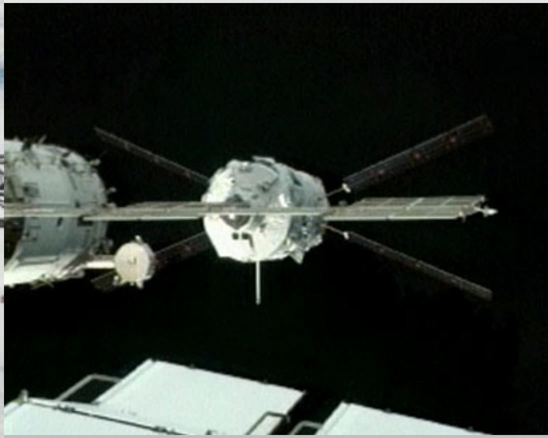
Smart-1 Li-Ion single cell batteries (5) 150Wh, 1.5kg

Control Systems 1/2

- Onboard control systems perform precision management of a satellite's orientation and position in space.
- In such a closed-loop control system, a set of sensors monitors the output - for example, the satellite pointing direction, or the space vehicle relative position - and feeds the data to a computer which continuously adjusts the control input through actuators, in order to maintain the desired pointing orientation or relative position.
- Feedback on how the system is performing allows the controller in the onboard computer to compensate dynamically for disturbances to the system.
- In this discipline the space applications include satellite attitude and orbit control, antennas or optical terminal fine pointing, and more generally guidance, navigation and control for space vehicles that have to accomplish specialized functions such as formation flying and orbital rendezvous, landing on asteroids and planetary bodies as well as re-entry through Earths atmosphere.



Huygens landing on Titan
http://www.youtube.com/watch?v=KpQLodJAgMk

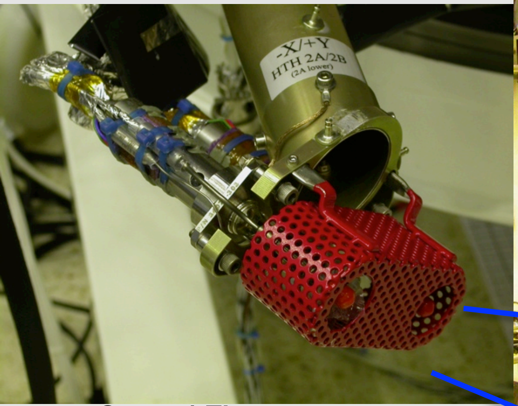


ATV docking to ISS
http://www.youtube.com/watch?v=m0TbGyIGv_0

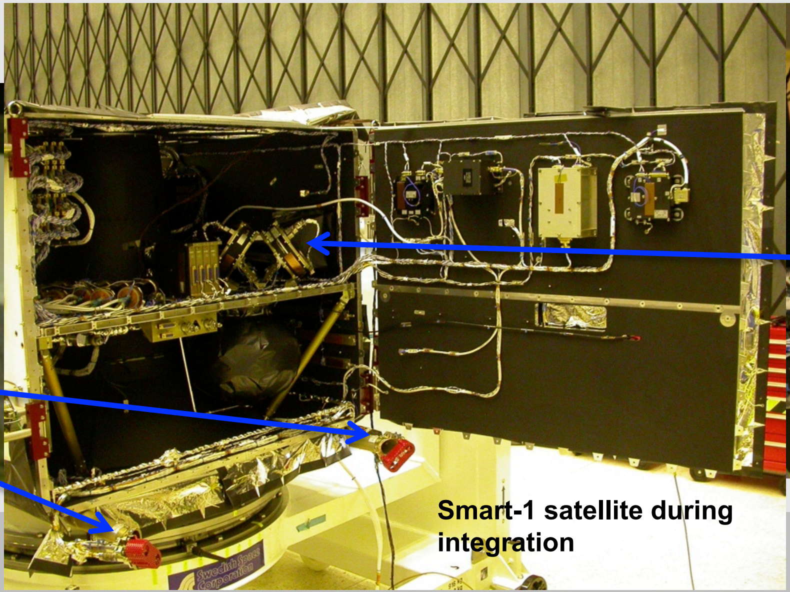
Control Systems 2/2

- The Attitude and Orbit Control Systems (AOCS) is in charge of controlling the spacecraft's pointing direction – known as its attitude – as it proceeds along its orbital path.
- Satellites have their attitude perturbed in various ways, whether by airdrag from the outermost layers of the atmosphere or Earths gravitational influence or solar radiation pressure exerted on large appendages, or interaction between Earth's magnetic field and satellite magnetic dipoles. A satellite attitude can also be disturbed by its own contents which can produce undesirable vibrations - liquid sloshing in a propellant tank and movements of large mechanisms are classical examples.
- The perturbing effects of such external and internal torques need then to be counteracted by the AOCS. In order to to identify the satellite's current attitude the system incorporates
  - sensors, such as Gyroscopes, Startrackers, Sun Sensors or Magnetometers
  - and actuators such as Thrusters, Reaction Wheels or Magnetic Torquers

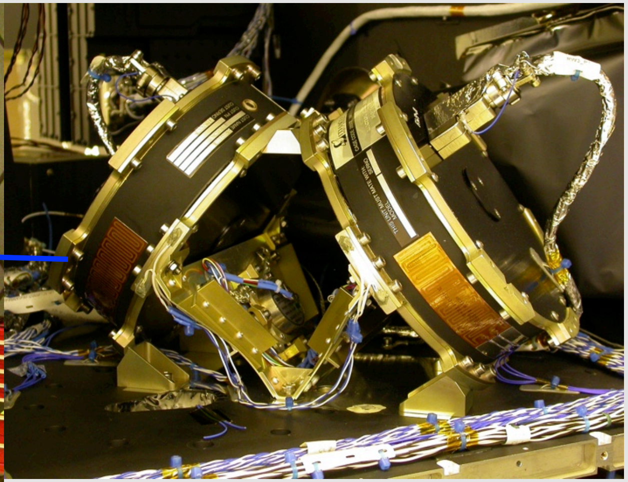
are used to trigger the desired corrective rotations around the satellites center of mass.



Smart-1 Thrusters



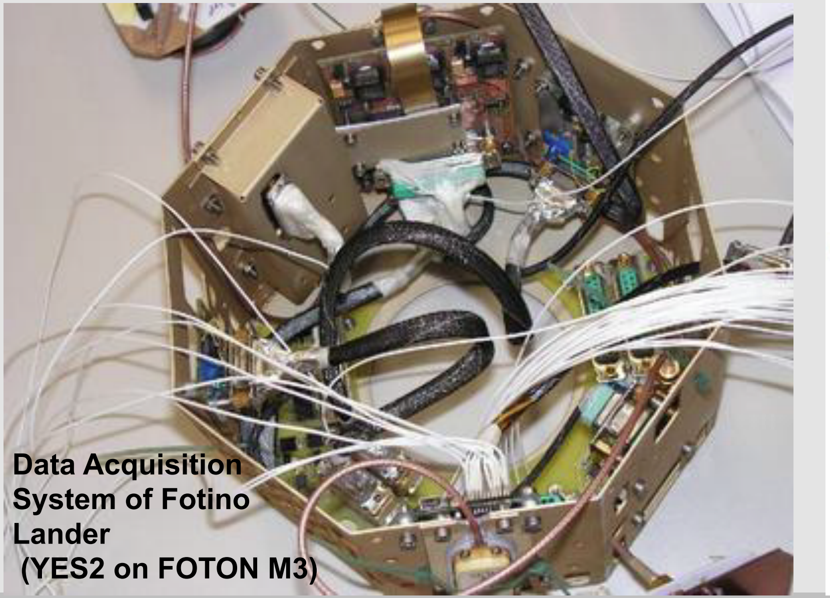
Smart-1 satellite during integration



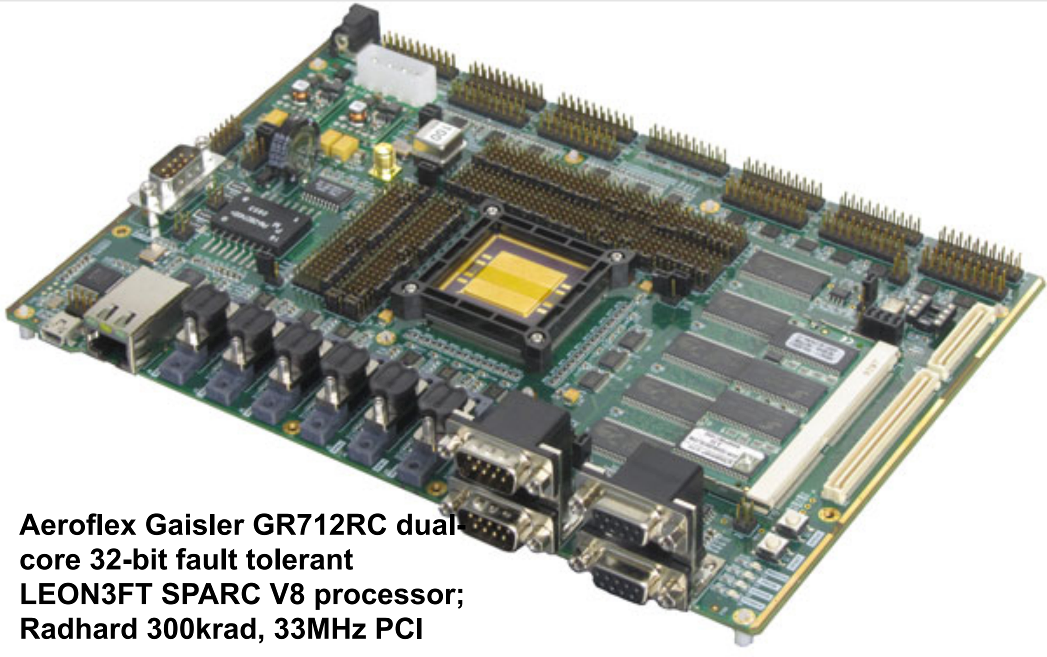
Smart-1 Reaction Wheels

Data Systems

- A satellite in space produces plenty of information. Data is continuously streaming from its instruments and subsystems, needing to be processed, stored and passed back to Earth.
- Data Systems deals with the technologies involved in a spacecraft's onboard data handling system. Besides handling Telecommands sent from ground for control purposes and gathering housekeeping Telemetry in return, it manages the information being produced, stored and conditioned on-board to allow downlinking to Earth.
- Data Systems touches on all aspects of onboard data management, including overall system architecture, hardware and software design and development of the underlying microelectronics building blocks.



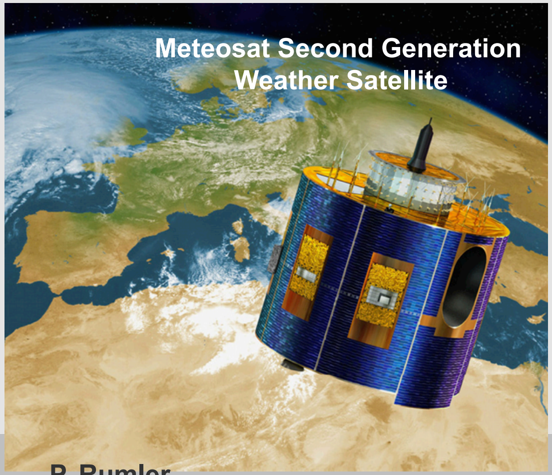
Data Acquisition System of Fotino Lander (YES2 on FOTON M3)



Aeroflex Gaisler GR712RC dual-core 32-bit fault tolerant LEON3FT SPARC V8 processor; Radhard 300krad, 33MHz PCI

Radio Frequency Systems

- Microwave radio signals serve as the backbone of communication between space systems and the ground, and are mainly used in:
  - Telecommunication satellites, which form the largest part of the currently around 2500 satellites orbiting earth.
  - Whether on an active or passive basis, radio signals also function as a remote sensing tool for scientific observation and environmental monitoring on space science and Earth observation missions.
  - Space-based radio navigation signals returned back to Earth form the basis of increasingly indispensable Sat-Nav systems (GPS, GLONASS, Galileo).
- Frequency ranges used:
  - Classical satellite communication uses S-band (1.98-2.2GHz) or lately X-band (7.9-8.4GHz)
  - Communication payloads on telecommunication satellites operate in C-band (3.7-6.4GHz), X-band, and Ku-band (10.95-14.5GHz)
  - Scientific and remote sensing instruments operate on the radio spectrum up to microwave (1-30Ghz) or millimeter-wave frequencies (30-100GHz) and.



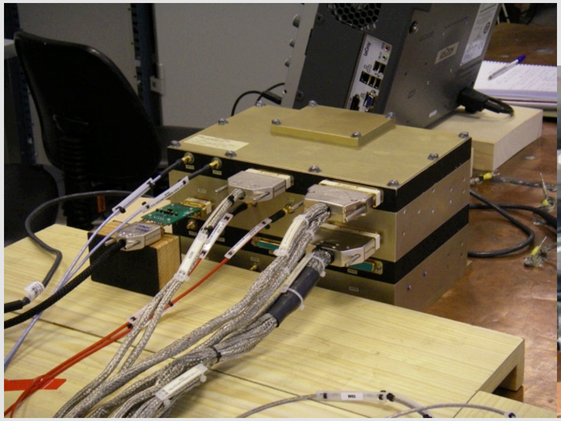
Meteosat Second Generation Weather Satellite

Alphasat Telecom Satellite

DSN 70m Ground Station Antenna

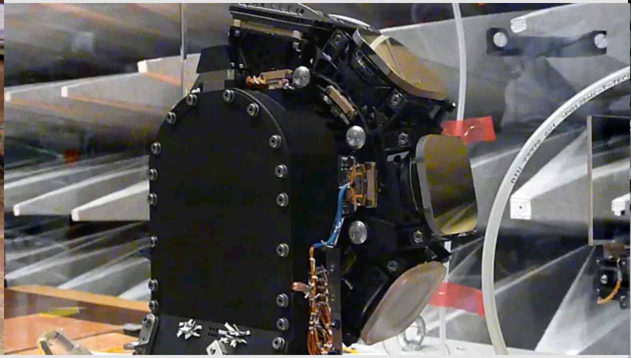
Electromagnetics and Space Environment 1/2

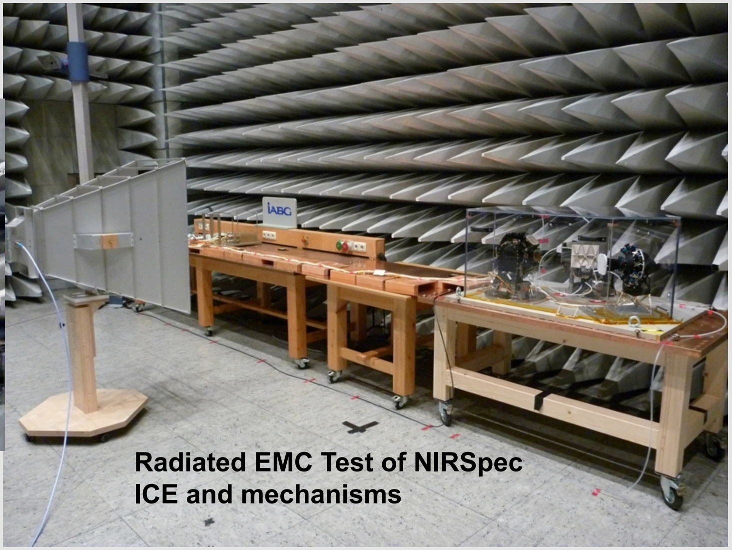
- Electromagnetics is concerned with issues of electromagnetic transmission, reception, propagation and interaction and Space Environment deals with the troublesome effects of the orbital environment.
- All spacecraft require electromagnetic compatibility (EMC) between their various equipment and subsystems, which generally demands a dedicated test campaign. For a complex and densely populated satellite accurate modeling of the electromagnetic fields often cannot be done and compatibility testing is needed. For this the conducted and radiated electromagnetic emissions are measured and higher levels are injected in order to determine if the system is robust.
- Antennas are the single most sensitive satellite element to interference, because they operate by deliberately turning electromagnetic fields into electric currents and vice versa. Modeling and testing can determine how spacecraft designs might affect antenna performance, taking account of adjacent electrical fields, reflecting surfaces and other potential radio frequency interactions.



Conducted EMC Test of NIRSpec Instrument Control Electronic (ICE) box

NIRSpec Grating Wheel Assembly (GWA) during Radiated EMC Test

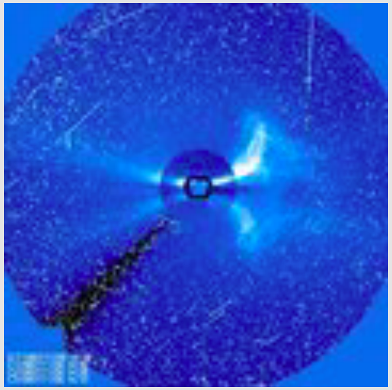




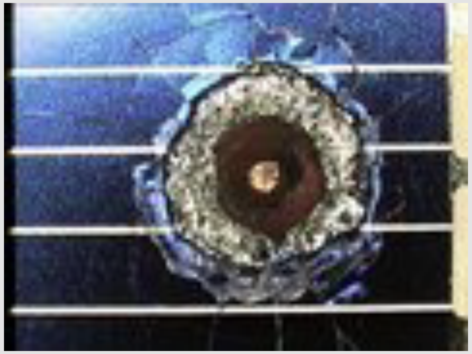
Radiated EMC Test of NIRSpec ICE and mechanisms

Electromagnetics and Space Environment 2/2

- The natural space environment consists of high energy particle radiation, plasmas, gases, and particulates and this domain includes evaluations of these environments and their effects on space systems.
- The radiation environment, consisting of 'trapped' radiation belts, cosmic rays, and solar energetic particles causes effects such as radiation damage, single-event upsets in electronics, background noise in detectors, and health hazards to astronauts. Mathematical modeling is used to predict for each mission and orbit the radiation environment and effects. With this input data the satellite manufacturer can determine the necessary shielding and predict interactions, determine the total dose and single event effects for electronic parts, assess materials and components degradation, sensor background noise, and astronaut hazards;
- Another phenomenon is the plasma environment which increases electrostatic charging of spacecraft parts or affects scientific instruments. And recently also the effects of electric propulsion have to be considered.
- Micro-meteoroids and space debris environments cause significant risks for manned and unmanned spacecraft. Space debris tracking databases have been established (http://www.youtube.com/watch?v=ElsubVLN9uE) and in-flight data on impacts is used to develop models and risk assessment tools.



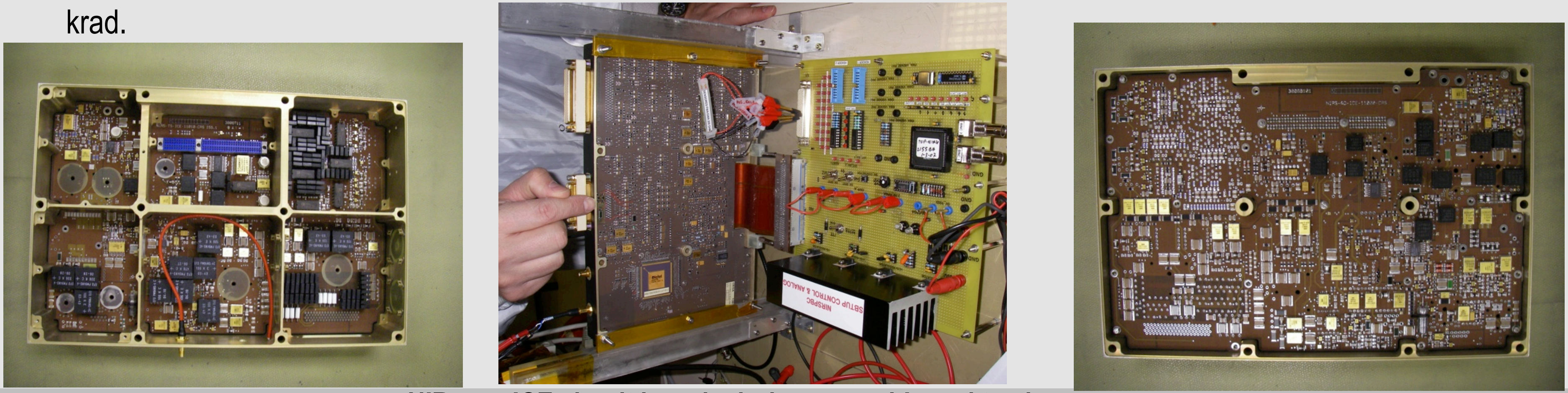
SOHO/LASCO coronagraph image showing contamination by energetic particles associated with solar activity



Impact crater (size 4 mm) on solar cell retrieved from space

Dependability of Electrical Circuits

- For most parts in space there is no possibility for repair (exceptions are ISS and Hubble)
- Therefore it is necessary to make reliable and maintenance-free items for space, starting from electronic components to satellite systems. This is achieved by:
- Redundancy: cold, hot or majority voting (2 out of 3), depending on the importance of the function.
- Failure Modes and Effects Analysis (FMEA): is used to analyze electronic circuits for potential failure sources and weak design (failure propagation) - provides inputs for design improvements.
- Worst Case Analysis (WCA): determines minimum performance of circuitry when considering component ageing, min/max thermal environment and end-of-life radiation.
- Parts Stress Analysis (PSA): checks that parts are not used above their de-rated specs in normal conditions and not above their specs in case of failures of adjacent parts – in order to prevent failure propagation.
- De-rating of parts: Most parts for space cannot be used up to their full spec levels, in order to preserve and extend lifetime. Example: capacitor maximum allowed temperature is 110°C, or 40°C below the manufacturer’s specified maximum.
- Use of radhard parts: Depending on the radiation environment and sector analysis parts have to withstand at least 20-100 krad.



NIRspec ICE circuit boards during assembly and testing

ELIXIR Training School

ELECTRICAL and TESTING

Part 2 - TESTING

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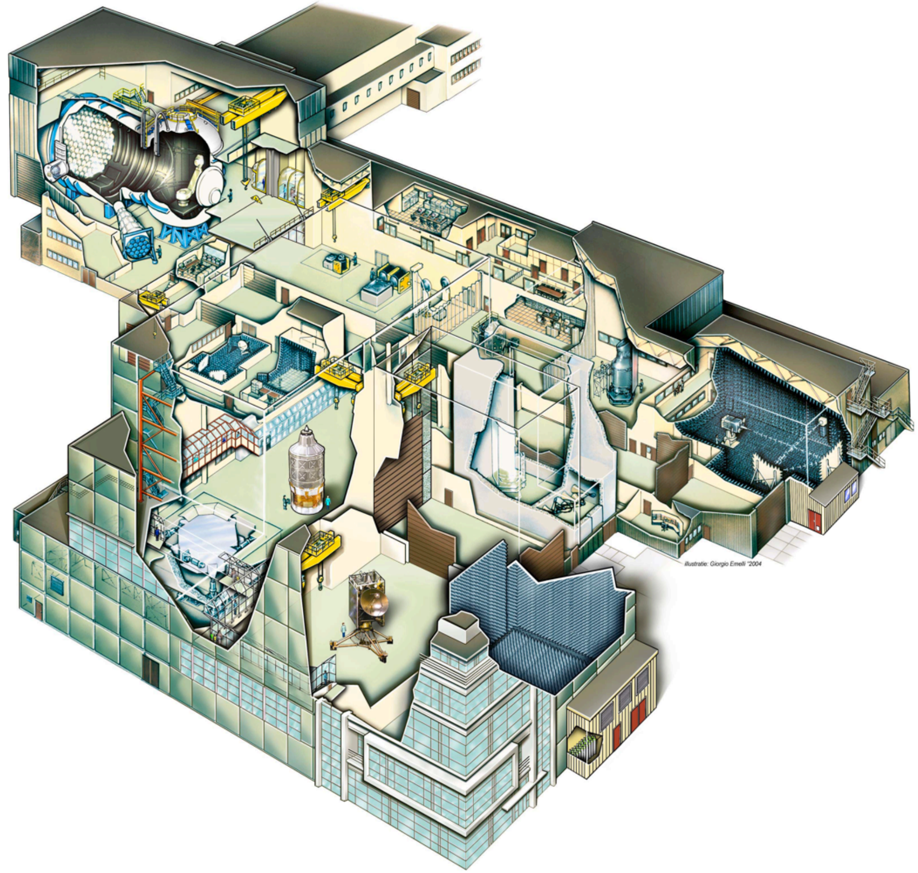
    - Maxwell EMC Chamber & CATR
  - <u>Solar Array Deployment Test</u>

ESTEC Test Center Overview

- Satellites are expensive, and once in orbit they cannot be fixed. Therefore a satellite and its component parts undergo extensive testing, in order to verify and validate their design. The majority of ESA spacecraft are tested in the ESTEC Test Centre.
- Based in ESA's ESTEC site in Noordwijk, the Test Centre is the largest center of its kind in Europe, and one of the largest in the world.
- It comprises a suite of state-of-the-art test facilities together with associated support elements such as check-out rooms, and highly-trained staff. It has been designed so that hardware – up to and including complete satellites - under test can be moved directly from one facility to the other without the need for reconfiguring it between tests and minimizing handling time.
- The ESTEC Test Centre is operated by European Test Services (ETS) on behalf of ESA. While the Test Centre is used extensively by ESA's own projects, it is also available to serve the needs of outside organizations.
- ESTEC Test Centre virtual tour: http://esamultimedia.esa.int/multimedia/ESTEC/virtualtour/



Cutaway drawing of the ESTEC Test Centre. The Large Space Simulator (LSS) is visible at the upper left.

Mechanical Environment Testing

- The first challenge for a satellite is its launch. To verify it will not be damaged the satellite is exposed to the severe vibration experienced during take-off, using the Test Centre's shaker tables. And in the LEAF satellites are exposed to the tremendous acoustic noise a launcher generates.
- There are three characteristic modes of vibration testing that are carried out – 'sine' testing involves subjecting the test item to a progressive sweep of frequencies and amplitudes. 'Random' testing randomizes this progression while 'shock' testing induces a sudden severe excitation, simulating the shocks felt during stage separations and engine firings.

- **QUAD system** – This facility is used to perform tests in a vertical direction on the largest or heaviest specimens (10 ton). The force is provided by four 160kN shakers. The specimen is fixed to the shakers by means of a magnesium QUAD-head expander with an outside dimension of more than 3m.
- **Multishaker –** this facility is built of two 160 kN shakers coupled to a large slip table. It can efficiently and safely test spacecraft with a mass of 10,000 kg in horizontal directions. The Two 160 kN shakers can also be used individually for testing subsystems in vertical configuration.

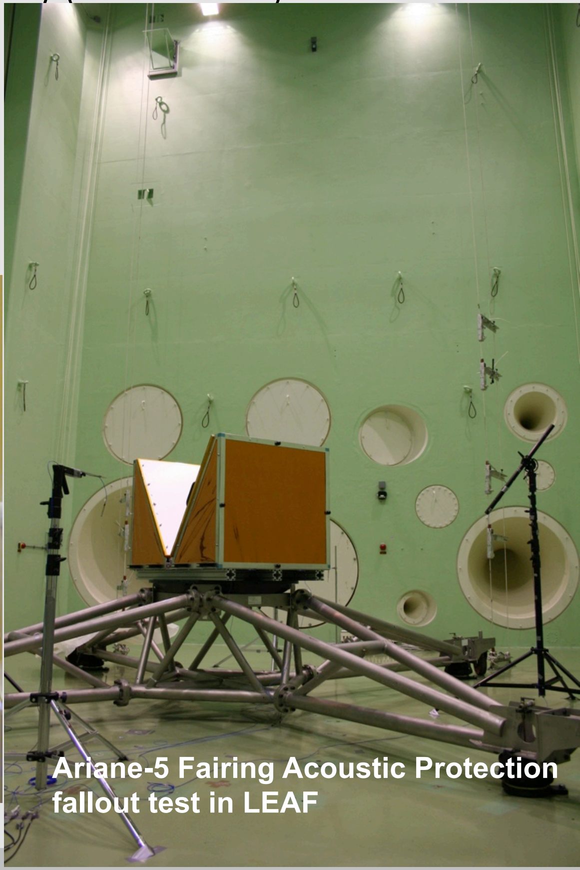
Galileo IOV on QUAD shaker

Aeolus Structural Model on the Multishaker

Mechanical Environment Testing 2/2

- The largest European facility of its kind, the **Large European Acoustic Facility (LEAF)** is a test chamber measuring 11 m wide by 9 m deep and 16.4 m high. Its walls are made of steel-reinforced concrete 0.5 m thick to contain the sound and are coated with a thick coating of epoxy resin to reduce noise absorption and increase internal reverberation.
- One wall is fitted with noise horns of the same basic design as those seen in stereo speakers which can produce noise equivalent to multiple jet aircraft lifting off simultaneously from 30 meters away (156 decibels).
- European spacecraft of all shapes and sizes undergo acoustic testing in the LEAF facility, up to and including the double decker bus sized Automated Transfer Vehicle (ATV). LEAF was originally commissioned in 1990, and build to fit the largest Ariane-5 Fairing.
- The main objective is to reproduce realistic spectral noise pressure levels, comparable to those generated by the launcher engines and by the airflow passing along the fairing during atmospheric flight.

Automated Transfer Vehicle (ATV) undergoing preparation for testing in the clean room outside LEAF



Ariane-5 Fairing Acoustic Protection fallout test in LEAF

Other Test Facilities – Centrifuge at NASA GSFC

- The **NASA High-Capacity Centrifuge** simulates the increased feeling of gravity's pull during a launch. For astronauts, that's normally a few minutes at two or three times the force of Earth's gravity, measured in g. Equipment carried in space shuttle cargo bays usually sees between 6 and 7 g because of vibration.
- The 120-foot-diameter (36.5m) centrifuge can accelerate a 2.5-ton payload up to 30 g, well beyond the force experienced in a launch.

- NASA technicians spun the Global Precipitation Monitor (GPM) satellite up to just over 10 RPM in Goddard Space Flight Center's High-Capacity Centrifuge facility March 31, 2011. At that speed, the spin exerted a lateral pressure of 2.4 g.
- The 2.4 g experienced by GPM would be sufficient to prevent blood from flowing up into a person's brain, inducing blackout if sustained.

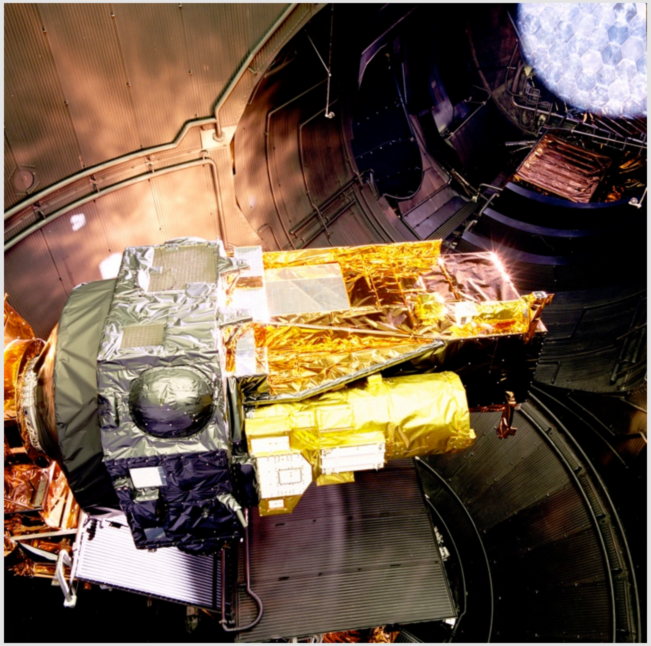
GPM on High-capacity Centrifuge

Thermal and Vacuum Testing 1/2

In the space simulation facility, test engineers expose the satellite to the vacuum conditions and the extreme temperatures of space for weeks at a time. This activity checks whether the satellite will continue to function properly in these conditions. Intensive testing goes on for months until ESA is convinced that the satellite is capable of performing well for the whole of its planned lifetime.

The **Large Space Simulator (LSS)** includes sun simulation and has a main vertical cylinder, the top flange of which forms a removable lid for easy loading into the chamber. An additional 5-m door is also available on the lower test-floor level.

The Sun simulator provides a horizontal solar beam of 6-m diameter and an intensity level of one solar constant (1380 W/m2) can be produced by operating 12 of 19 xenon lamp modules at a nominal power of 20 kW per lamp. With all lamps at full power, a flux in excess of 2700 W/m2 can be achieved.



INTEGRAL in LSS with sun simulation

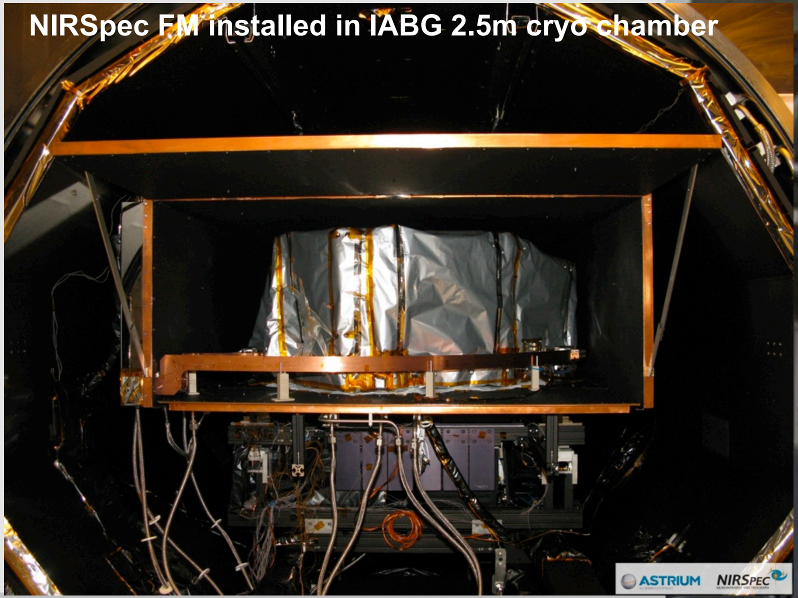
METOP is loaded into LSS from the top

http://www.esa.int/esaMI/Space_Engineering/SEM2MWZO0WF_1.html

Thermal Facilities								
name	volume	Length	diameter	Lower T	Upper T	Vacuum limit	Sun diameter	Sun intensity
Phenix	160 m3	10 m	4.5 m	100 K	373 K	< 5e-6 mbar		
LSS	2300 m3	10 m	9.5 m	100 K	350 K	< 5e-6 mbar	6 m	2800 W/m2

Thermal and Vacuum Testing 2/2

- The purpose of TV testing is to expose payloads or complete spacecraft to representative space conditions – a vacuum state combined with repeated cycling between high and low thermal extremes – in order to assess their likely flight performance.
- Phenix is the new thermal vacuum test chamber which replaces the ESTEC HBF-3 facility, now dismounted. It performs similar testing to the Large Space Simulator (LSS), but on a smaller scale and without a solar simulator lamp.
- In this chamber test items are placed within a thermal tent before, which is then slid into the vacuum chamber on a trolley system. Measuring 4.2 m long by 2.5 m wide and 3 m high, the thermal tent is made of copper plates with brazed copper pipes which use liquid and gaseous nitrogen to produce the range of temperatures desired, from +100°C to less than –170°C.
- The JWST NIRSpec Instrument TV testing is performed in a similar 2.5 m chamber in IABG (Munich).
- In addition, this chamber is equipped with a closed gaseous He cooling system which allows test temperatures down to 10 K. By using the He cooling system the He shrouds and up to 3 thermal plates can be individually temperature controlled in a range of 10-320 K.


NIRSpec FM installed in IABG 2.5m cryo chamber


ESTEC Phenix thermal vacuum chamber

Other Test Facilities – JSC Chamber A

- For comparison: Large Space Chamber A in Johnston Space Center, Houston, Texas
- Built in the early 1960's for Apollo manned spacecraft testing and currently under refurbishment for JWST OTIS (Optical Telescope + ISIM) testing; size = 16.8 m diameter x 27.4 m high

Chamber A modifications for JWST

JSC CHAMBER A MODIFICATIONS FOR JWST

NITROGEN DISTRIBUTION

Provides 80K to 358K LN2 to Shroud He Cold Box, Cryo Pumps
- LN2 storage tanks
- Ambient vaporizers
- LN2 recovery cold box
- Steam trim heater
- 5 Phase separators
- Supply/return lines

AIR FLOW MANAGEMENT

Conditioning and contamination contol of in-chamber air
- Make-up air unit
- Filter coil air handler
- Blower
- Heater
- Ducting
- Large bore air-return piping

AMBIENT VAPORIZER FAB

This is a picture of one of the ambient vaporizers.

Just for scale, it will be about 7.5'x7.5'x24' when completed

CHAMBER A, MAY 2009

BEFORE

AFTER

Removal of 18 angle valve flanges, from diffusion pumps, from side of chamber

HELIUM DISTRIBUTION

Provides 15K to 333K gaseous He to the shroud
- Storage tanks
- Compressor system
- Oil removal system
- Heater
- Cold box
- Ambient vaporizer
- Supply/return Lines

HELIUM SHROUD

Provides 20 to 333 K environment to test article

NITROGEN SHROUD

90 to 358K environment and pumping capacity

RADIANT BARRIERS

Shield shrouds from chamber walls

POWER DISTRIBUTION

Normal and backup Power inside and outside chamber

RAIL SYSTEM

Supports test article in highbay and chamber

HIGH VACUUM SYSTEM

Achieve Chamber P of 10^{-2} Torr
- Roughing pumps
- Piping

Achieve 10^{-2} to 10^{-4} Torr
- 6 turbo-molecular pumps

Achieve 10^{-4} to $\leq 5\times10^{-6}$ Torr
- 12 cryo pumps
- Gate valves

VACUUM VESSEL HEAD

VACUUM VESSEL SHELL

HELIUM COLD BOX PIPE SPOOLS

ADSORBER VESSEL

HELIUM COLD BOX ASSEMBLED VESSEL

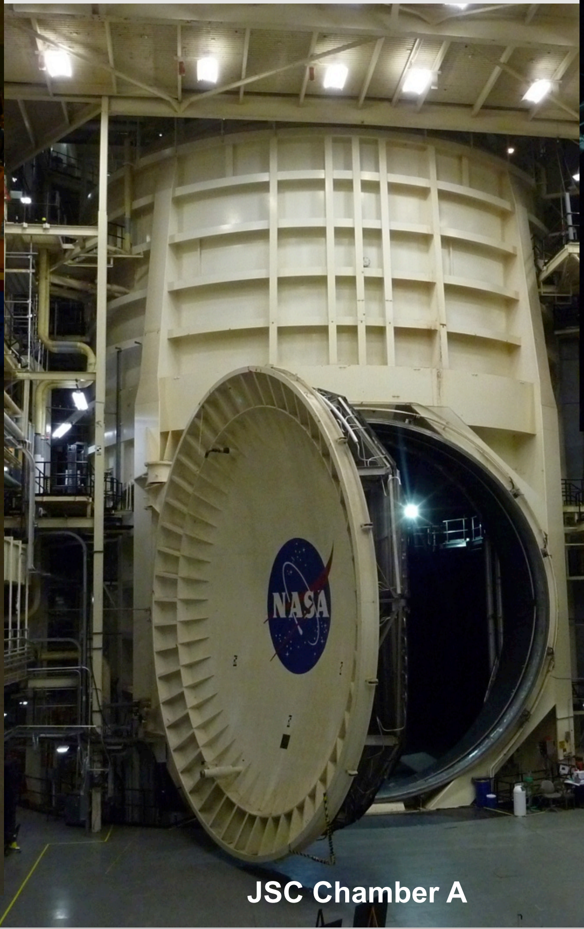
LARGE BORE PIPE INSTALLATION

To reroute air flow path from chamber bottom entry to top entry

NORTH SIDE PLATFORM INSTALLATION

NORTH SIDE PAINT ABATEMENT

TOP SUN SHROUD



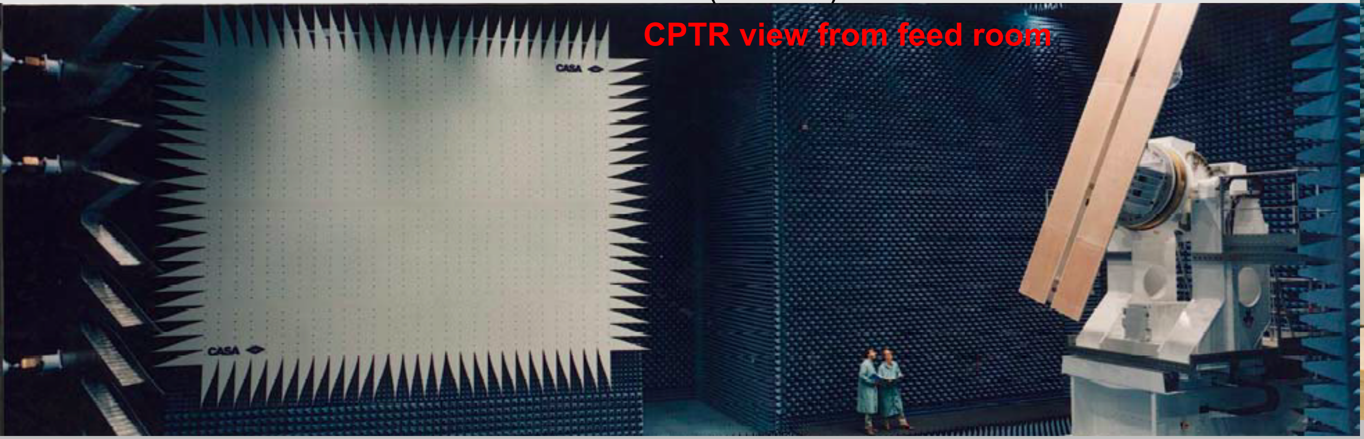
JSC Chamber A

View from top of interior

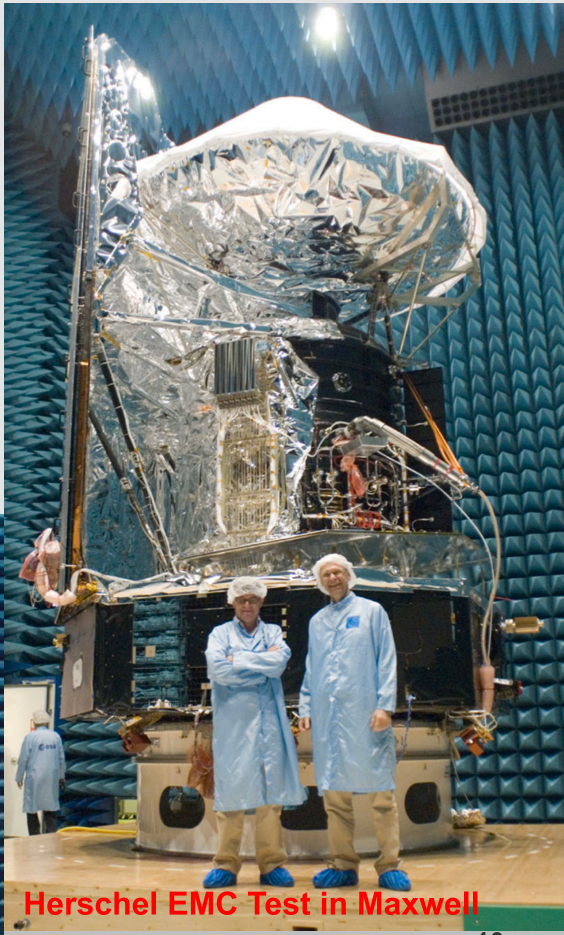
http://www.nasa.gov/centers/johnson/engineering/integrated_environments/altitude_environmental/chamber_A/index.html

Electromagnetic Compatibility Testing

- The **ESTEC Maxwell Test Chamber** is our EMC facility for the largest spacecrafts in Europe (like ATV), with chamber dimensions of 14.5 x 10.7 x 11 m (LxWxH).
- The chamber consists of a shielded enclosure, commonly called a Faraday cage, with continuously conducting metal walls, floors, and ceilings. The walls and ceiling are lined with an absorbent, anechoic material designed to attenuate the reflected electromagnetic energy. The floor is lined with ferrite absorbers and mobile resistive absorbers.
- The wall opposite the main door is lined with air-cooled high-power resistive absorbers capable of dissipating up to 3 W/cm^2. Ceiling and floor absorbers are specially coated to prevent particle release so as to preserve the class 100 000 cleanliness level (ISO 8).
- The ESTEC **Compact Payload Test Range (CPTR)** is an antenna test facility for measurements on larger antennas or complete satellite payloads.
- This "compact" anechoic chamber incorporates parabolic reflectors which are specially shaped to straighten the curvature of the radio waves, artificially creating equivalent conditions to space transmissions within a relatively small area. CPTR dimensions: 25 x 16 x 11 m (LxWxH)



CPTR view from feed room



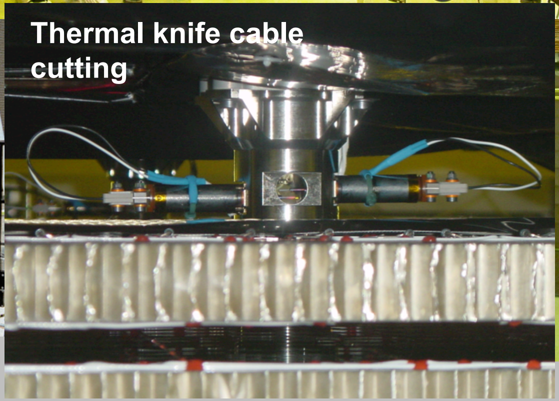
Herschel EMC Test in Maxwell

Solar Array Deployment Test

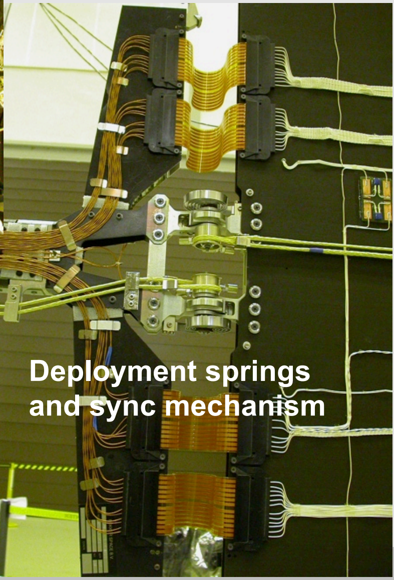
- Solar Arrays are normally deployed after spacecraft separation from the launcher in vacuum and near zero-g conditions. When deployed, they are not built to carry their own weight in 1g on the ground.
- In order to test the deployment and its release mechanism, special deployment rigs have to be installed, that carry the weight and guide the deployment.
- Deployment is released by pyrotechnic actuators or thermal knife cutting, and driven by springs. And the end of deployment shock can be counteracted by eddy current dampers.

Smart-1 Solar Array deployment test

Integral Solar Array in deployment rig

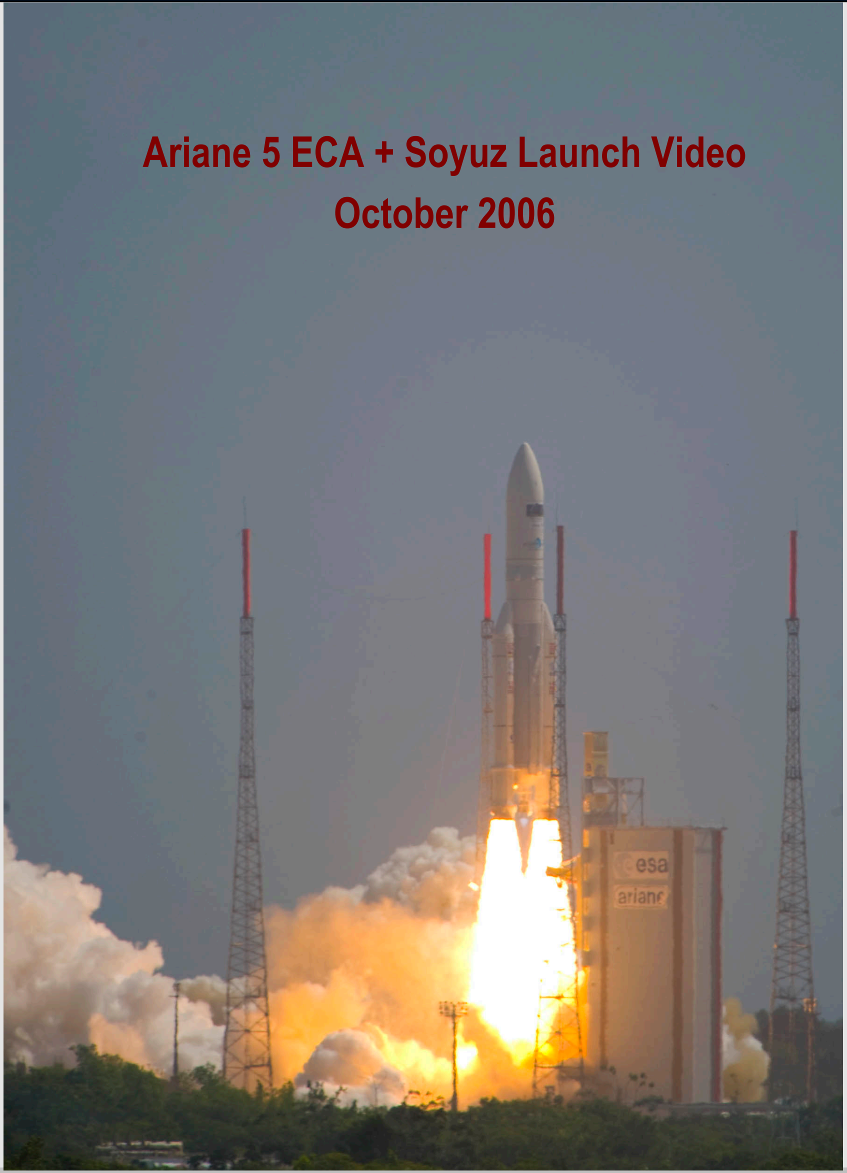


Thermal knife cable cutting



Deployment springs and sync mechanism

The End



Ariane 5 ECA + Soyuz Launch Video
October 2006