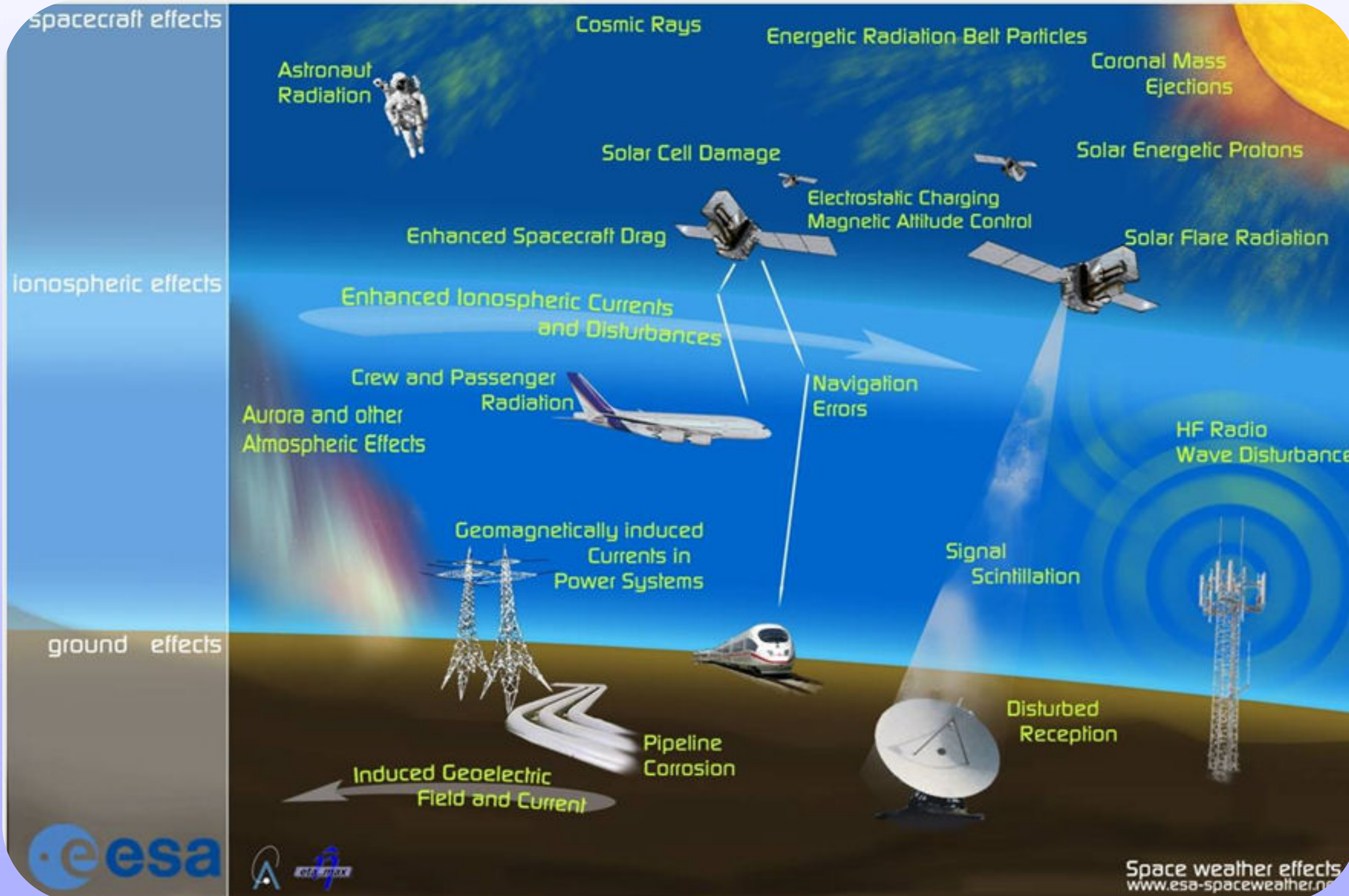
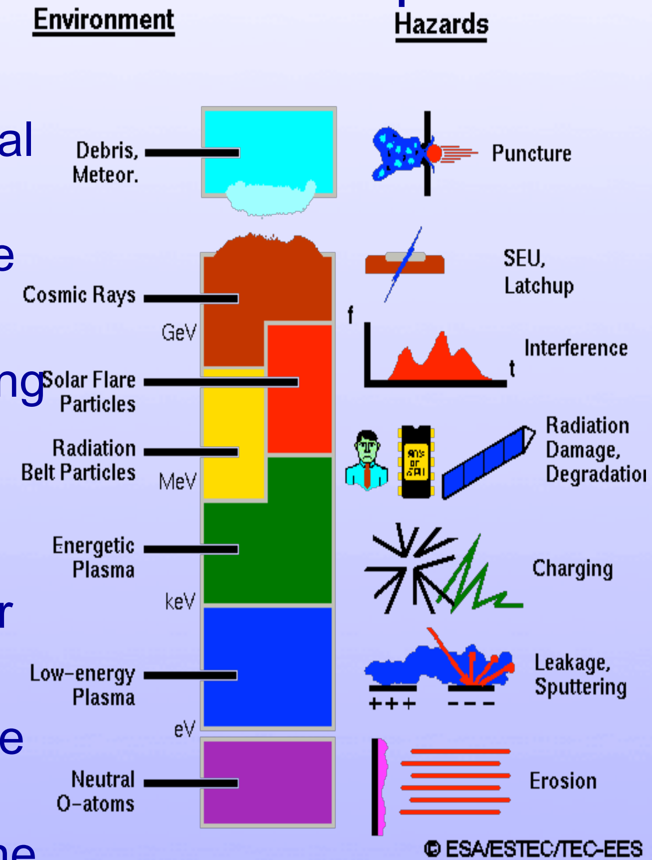
Effects on Spacecraft



Effetti su Spacecraft

The space environment consists of many hazards. Most of these hazards have specific effects on spacecraft and their components

- **Radiation**: Van Allen belts, source of energetic charged particles, surround the Earth. Sun activity create additional energetic particles in sudden bursts. High energy heavy charged particles reach the Earth vicinity from outside the solar system
- **Plasma, ionised gases around Earth**: electrostatic charging of surfaces when energetic plasma is injected near the busy GEO (magnetospheric storms/substorms). Discharges can severely disturb operations. The cold ionospheric plasma is a problem for operating high power systems because of its conductivity
- **Micro-meteoroids and space debris** can seriously damage satellites (manned missions). Increasing space activities add to the space debris problem in popular orbits while the meteoroid environment is an ever-present sporadic feature
- **Others** environments include the residue of the atmosphere at low orbital altitudes including highly-reactive atomic oxygen, contamination, dust …



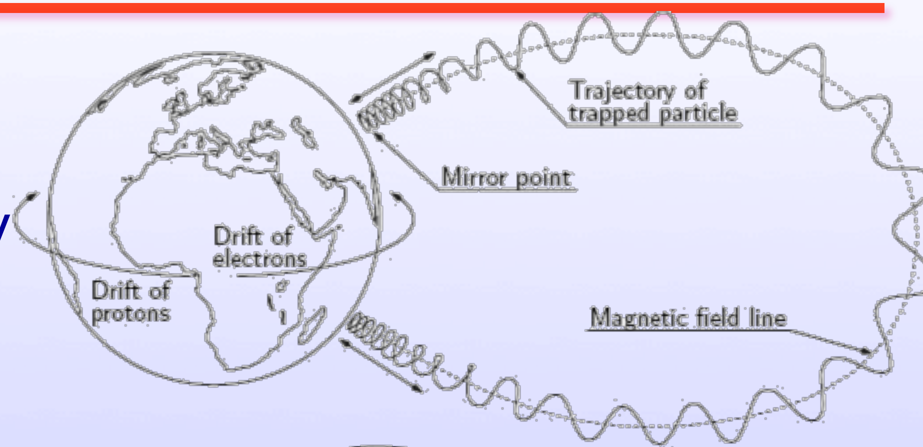
Space Environment

- Radiation
- Plasma
- Geomagnetic field
- Space debris
- Micro-particles & Meteorids
- Atomic Oxigen
- Contamination

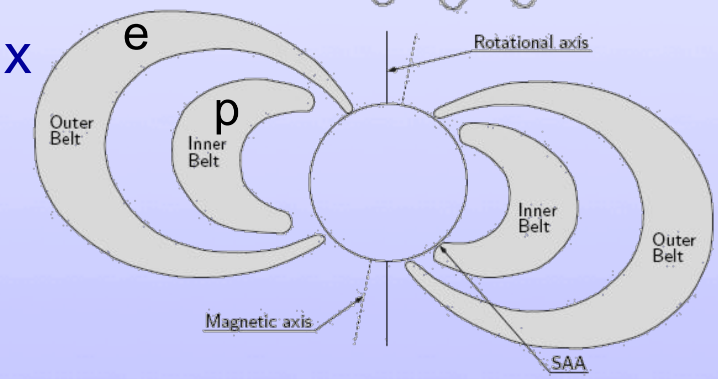
- SPENVIS

Radiation Environment

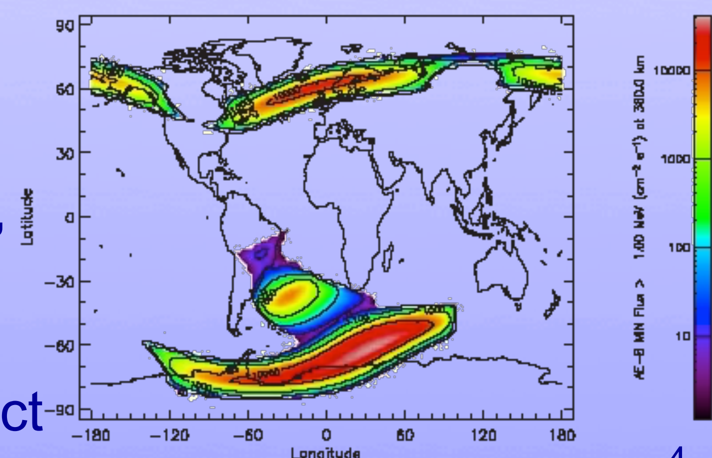
- Trapped particle belts
  - electrons of up to a few MeV
  - protons of up to several 100 MeV
  - low altitude (LEO)



- Solar particle events
  - large fluxes of energetic protons, peak flux in excess of ~10^6 p/cm^2/s, ≥10 MeV
  - Geomagnetic shielding but reach polar regions and high altitudes (GEO)



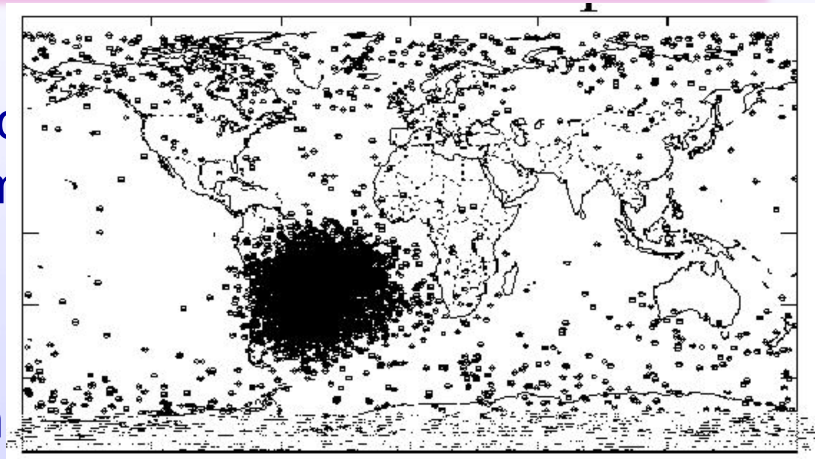
- Cosmic rays
  - originated outside the solar system, low fluxes but heavy-energetic ions (iron)
  - intense ionisation passing through matter, significant hazard (difficult to shield) for integrated electronic components, solar cells, interference and radiobiological effect



Radiation effects & analysis

- Degradation - radiation damage
  - induced by the ionisation that radiation causes in a material, defects created in the molecular structure of a material and similar displacement damage effects
- Single Event Upset (SEU)
  - from ionisation produced by energetic heavy ions through a sensitive part of a semiconductor chip, the free charge generated is sufficient to flip the logic state of the bit
  - from energetic protons/ions hitting a nucleus in a sensitive component location. The nuclear interaction produces spallation splitting the nucleus, the spallation products generate the ionisation flipping the bit state
- Radiation Background
  - interference with detectors (astronomy missions) increasing background
  - Interference from secondary radiation (γ-rays, $e^{\pm}$, ions) by interactions of primaries (bremsstrahlung, nuclear interactions). In optical components: energetic particles cause scintillation (fluorescence) and Cerenkov

Radiation effects & analysis



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Radiation effects & analysis

- Radiation is a concern for manned missions (low altitude, ISS)
  - The radiation risk due to highly ionising cosmic ray nuclei is of particular concern for astronauts especially for long flights such as those for the space station and for future inter-planetary missions. The radiation risk can be estimated base on the flux of particles as a function of their energy loss, LET (Linear Energy Transfer)

Radiation Analysis

Radiation can penetrate S/C walls and deposit 100s krads in certain orbits. Shielding: mass & cost (+showering)

- Trapped particle belts
  - AE8 and AP8 models for $e^{\pm}$ / protons, developed by Vette et al. (NSSDC @NASA/GSFC) based on data from '60s / '70s satellites. Omni-directional fluxes as functions of idealised geomagnetic dipole coordinates ($B/B_0,L$) (spenvis). Apart from for solar max and min versions, no description of the temporal behaviour of fluxes while at high altitudes (GEO) fluxes vary by orders of magnitude over short times and exhibit significant diurnal variations
  - New Trapped Radiation Environment Model. Data from Meteosat, CRRES and ISEE have been used to construct databases and subsequently new anisotropy models of energetic electron flux temporal and spatial characteristics taking into account strong directionality and link to atmospheric density

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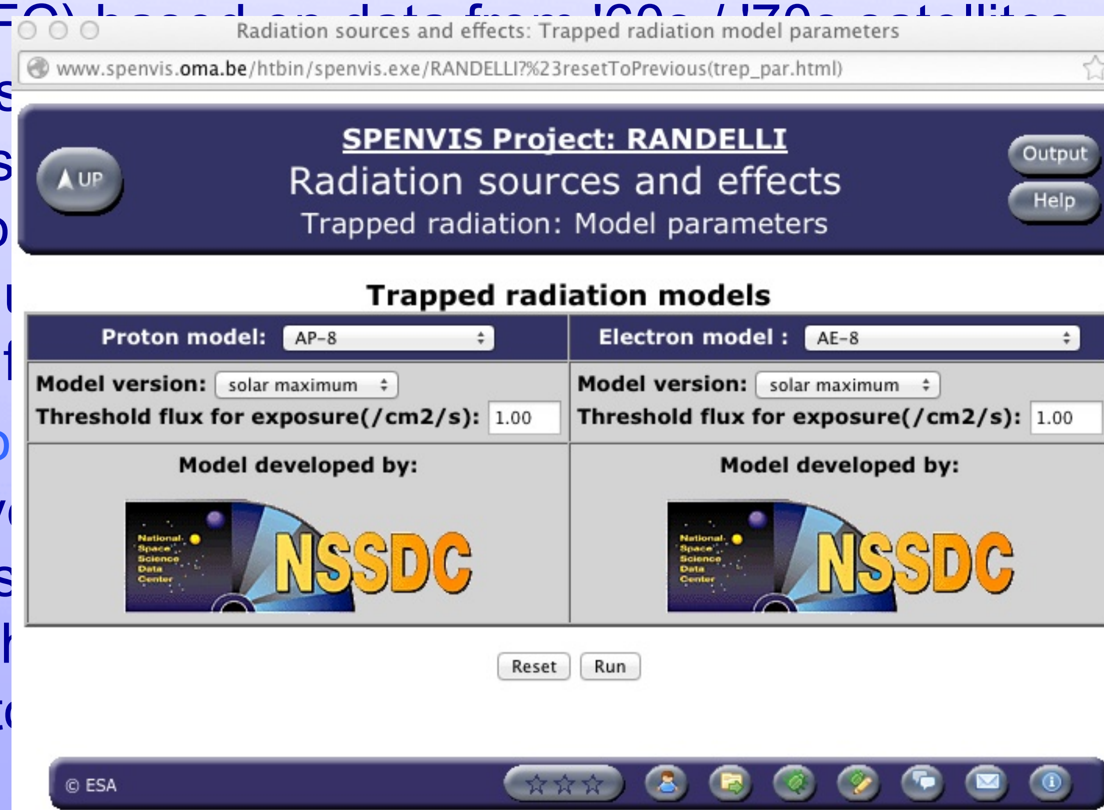


Radiation Analysis

- Solar particle events (SPE)
  - It is not possible to predict the exact occurrence, intensity or duration of SPE: mission planning can be problematic
  - Short-term forecasts are necessary for any tasks requiring extra-vehicular activity (EVA) and the operation of radiation-sensitive detectors
    - Sun real-time observation can provide useful warning of solar activity, as large proton events are usually associated with the strong emission of electromagnetic radiation (visible light, radio waves, soft X-rays)
  - Long-term predictions of the radiation levels resulting from events are derived from statistical models based on past observations
    - King model: standard model used to predict mission-integrated solar proton fluences
    - JPL (Feynman) model: recently recommended for use for future mission planning

Radiation Analysis

- Cosmic rays
  - CRÈME, Cosmic-Ray environment and effects models by Adams et al. @NRL: a comprehensive set of cosmic-ray and event ion LET and energy spectra, including treatment of geomagnetic shielding and material shielding
  - CREME also includes upset/hit rate computation based on the path length distribution in a sensitive volume and can also treat in a simple manner trapped proton-induced SEUs

Plasma Environment

- A body in a plasma (atmosphere) is subject to a flux of electrons (much more mobile) and ions
  - Surfaces charge negatively with respect to the local plasma (effect observed in laboratory plasmas and often in space), the surface continues to attempt to acquire the amount of charge necessary to establish a current balance until equilibrium is reached
  - In space, under solar UV and energetic particle irradiation, the balance includes secondary and photo-emitted electrons
  - As a consequence, the charging of spacecraft surfaces is a function of the energy distribution of the plasma (temperature), the area of the surfaces exposed to the Sun and the properties of the materials on the S/C surfaces

Plasma Effects

- High Altitude and polar orbits: electrostatic charging of S/C surfaces
  - Charging is the result of the attempt to achieve a balance of currents to surfaces corresponding to an equilibrium state:

    ion currents; secondary emission currents; back scatter currents; photo emission currents; $e^{\pm}$ currents; bulk currents

    $$I_e + I_i + I_{se} + I_b + I_{ph} + I_R = 0$$

  - currents are functions of the complex environment, simplified for Maxwell distribution
  - during geomagnetic substorms, hot plasma (10-30 keV) is introduced in GEO, currents also depend on surface potentials and electric fields on and around the S/C and on the material properties
  - testing and characterisation of materials are crucial for analysis (but space environment difficult to reproduce…)

Plasma Effects

- Low Altitude: cause leakage of power from exposed solar arrays and electromagnetic perturbations
  - The low-altitude plasma is cold and dense screening any S/C-generated electric field: surface charging to high potential level is normally not possible. S/C velocity is mesosonic (faster than ion but lower than electron thermal speed): ions are not fast enough to refill S/C back region and a ion current is collected on the front. Surfaces in the back can charge if exposed to energetic electron fluxes (auroral events)
  - Snap-over: elevated-voltage systems can drive current through the local plasma, current can be larger than expected because of plasma sheath geometry effects
  - Plasma interacts with electromagnetic waves. The dispersive properties and non-homogeneity of the ionospheric plasma can be a concern for several space-based systems (telecommunication device, GPS, RADAR)

Plasma Analysis

- **Charging** (large amount of input data and careful use)
  - Simple non-geometrical methods (MATCHG) can be used to predict a given material tendency to charge by solving the balance equation, also as a useful aid to interpretation of testing results. Tests include exposing material samples to mono-energetic electron beams and measuring surface potentials and currents
  - 3-dim models (NASCAP) include shadowing producing photo-emission differences, electric fields around the S/C affecting the currents striking or leaving a surface and inter-material currents which will affect their potentials
  - Spacecraft Plasma Interaction System (SPIS), used in parallel
- **Plasma** (close link of numerical simulation and experiments on S/C-plasma interactions)
  - POLAR & NASCAP/LEO: for assessing the problems of plasma interaction at low altitude. Same as NASCAP, same material properties but are applicable to short-Debye-length regimes (i.e. cold dense plasmas). POLAR: to evaluate charging expected in auroral oval while LEO to evaluate anomalous current collection – snapover

Geomagnetic Field Analysis

Geomagnetic field models required for trapped particle, solar event and cosmic-ray environment to include geomagnetic shielding effects

magnetic field strength

radial distance of the field line from the axis at the geomagnetic equator in an ideal dipole field

- Geomagnetic Field
  - Coordinates: at low altitude, field is approximately that of a magnetic dipole, at high altitude it is strongly distorted. Trapped particle morphologies are described in terms of location in idealised geomagnetic dipole space, as functions of energy and coordinates (B/B_0, L). L is defined as a function of the adiabatic integral invariant I, constant on a field line. By transforming orbital locations into (B,L), accessing the radiation environment models, predictions of satellite radiation exposures can be made
  - Non-dipolar contributions are important, best described by numerical models which account for the offset and tilt of the geomagnetic axis with respect to the Earth rotation axis. Despite the fact that the field is not a true dipole, (B, L) coordinates are valuable for describing locations and are adopted as the system for radiation environment analyses

Geomagnetic Field Analysis

- Geomagnetic Field
  - Models: numerical models describe the internal field and its secular variations by spherical harmonic expansions of the scalar potential *V*. A number of field models are available, the main ones are those in the International Geomagnetic Reference Field (IGRF) series:

$$V = a\sum_{n=1}^{k}\left(\frac{a}{r}\right)^{n+1}\sum_{m=0}^{n}\left[g_n^m\cos(m\Phi)+h_n^m\sin(m\Phi)\right]P_n^m(\theta)$$

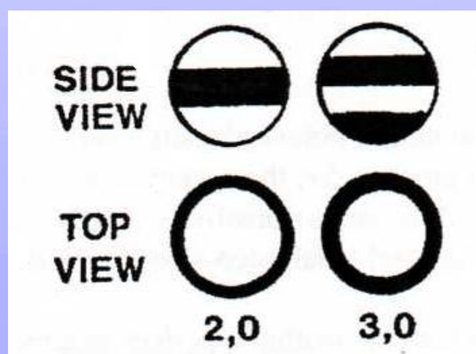
a = 6371.2 km

(r,θ,ϕ)

g(m,n), h(m,n) model coeff.

P(m,n) Schmitt-normalised Legendre functions

  - IGRF models released since 1960 have had 120 spherical harmonic coefficients (to degree and order 10) and a further 80 (to degree and order 8) describing the secular variations of the corresponding main field coefficients in a linear fashion



g(2,0) represents the flattening of Earth, meaning an additional ring of mass around the equator

g(3,0) is presenting the "pear" shape of Earth, meaning additional mass at the South pole and the northern mid-latitudes

Geomagnetic Field Analysis

- Geomagnetic Field
  - External field model: the models describe the field generated by processes within Earth. At high altitudes most of the higher-order terms become negligible and the dipole approximation is often adequate to describe this contribution, BUT, the solar wind causes large diurnal distortions of the field
  - This effect, together with the ring current from azimuthally drifting particles, and other current systems means that the internal field is a poor representation of the total field
  - Various models for the external contributions, including the diurnal asymmetry of the field and depend on geomagnetic activity indices, developed by: Tsyganenko, Olsen and Pfitzer, Mead and Fairfield. The CRRES programme is also planning to use external field models in analysis of energetic particle data

Space Debris

Space debris is man-made, growing in numbers. Long lifetime due to the small amount of the perturbing forces (atmospheric drag, gravitational attraction of Earth, Moon, Sun). Four parts:

- Fragmentation debris
  - Breakups are destructive events that generate numerous smaller objects with a wide range of orbital parameters. Products of deterioration can be large enough to be detected from Earth. Parts of the S/C are detaching and become space debris (thermal blankets, protective shields, parts of solar panels). Deterioration is the result of the harsh space environment (thermal cycling, atomic oxygen). Fragmentation material is the single largest component of the tracked space debris population, accountable for over 40% of space debris
- Non-functional spacecraft
  - S/C that are intact structures having completed their mission, or satellites which had a non-destructive malfunction that shortened their lifetime. This group is accountable for 25% of space debris

Space Debris

- Rocket bodies
  - Rocket bodies are of particular importance for the future evolution of the space debris population, due to their large dimension and the potentially explosive residual propellant. With the deployment of a satellite mission, many parts of the launcher become space debris
- Mission related debris
  - Items related to the functional operation of the satellite itself: explosive bolts, vehicle shrouds and lids covering telescopes and other fragile equipment. This comprises all man-made items of space flight: exhaust products from Solid Rocket Motors (SRM), paint flakes, Radar Ocean Reconnaissance SATellite (RORSAT) droplets, Westford needles:
    - SRM can release droplets, such as Al_2O_3, particles are generally small (diameters from 0.1 μm to 3 cm) but flux rate is high
    - Paint flakes, de-attached from S/C, are the result of the harsh space temperature environment
    - The RORSAT droplets are coolant droplets from the Russian RORSAT satellites. These inactive satellites released coolant droplets (NaK, liquid metal) from the nuclear reactor when it was separated from the S/C

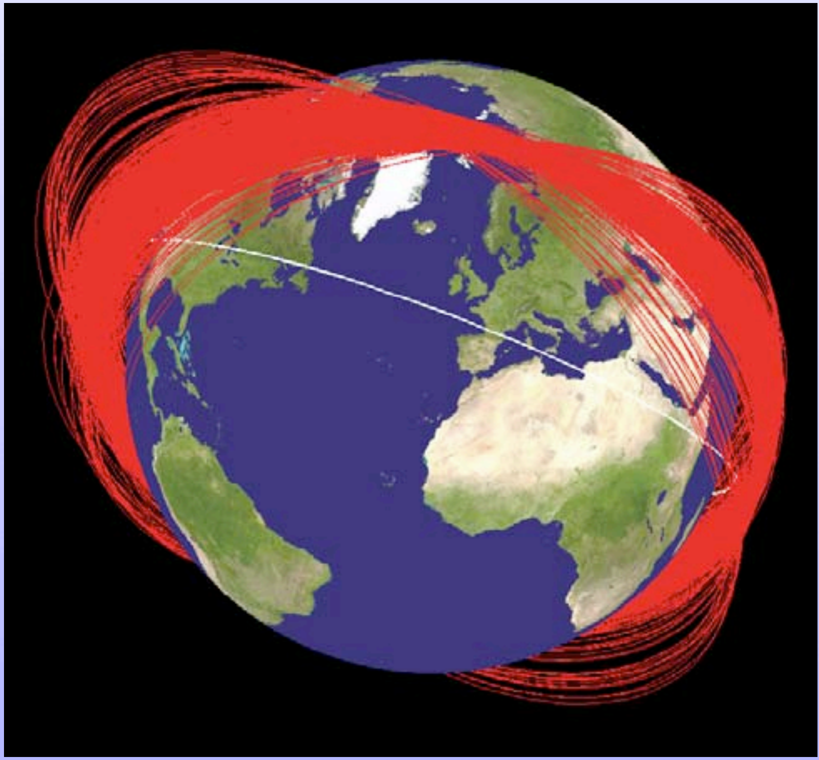
Space Debris

- Mission related debris
  - Westford needles was a project of DoD, 1962. A large number of copper needles were intentionally released in an attempt to lay a radio-reflective ring around the Earth, like dipoles as an artificial scattering medium for radio signals in the cm band. The experiment was greatly criticized by astronomers who feared optical and radio pollution. The 1st experiment did not work as a radio reflector, the 2nd one was successful, new needle populations are discovered by radar and optical measurements
  - Mission related debris is generally small in diameter. Therefore they are hard to detect with the current observation methods, which can trace space debris from a diameter of 10 cm and larger, depending on the debris altitude. The amount of released debris can be quite large. For example, 200 pieces of mission related space debris were linked to the Russian space station Mir during its first 8 years of operation. Most of the mission related debris was dumped intentionally, but there are also examples of astronauts who lost items during Extra-Vehicular Activity
  - “Mission related debris” is accountable for over 14% of space debris
- The remaining 2% of space debris has an unknown source

Space Debris

✦ 2007 Chinese anti-satellite missile test

- On January 11, 2007, China conducted an anti-satellite missile test. A Chinese weather satellite, the FY-1C polar orbit satellite of the Fengyun series, at an altitude of 865 km, with a mass of 750 kg, was destroyed by a kinetic kill vehicle traveling with a speed of 8 km/s in the opposite direction
- This event was the largest recorded creation of space debris in history with more than 2,000 pieces of trackable size (golf ball size and larger) officially cataloged in the immediate aftermath, and an estimated 150,000 debris particles
- They represent more than half of the tracked debris orbit the Earth with a mean altitude above 850 km, likely remain in orbit for decades or centuries
- In April 2011, debris from the Chinese test passed close by the ISS



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Micro-Meteoroids Environment

- The natural space environment comprises different natural macroscopic particles
  - Asteroid: a relative small body composed or rock, carbon or metal, orbiting the Sun
  - Comet: a relative small body, composed of dirt and ice. Comets are characterized by tails of dust and gas, when the comet is near the Sun. Far away from the Sun, comets look similar to asteroids
  - Meteoroid: a small particle originating from an asteroid or comet, usually orbiting the Sun
  - Meteor: the light trail of a meteoroid burning up in the atmosphere of Earth. This burning is visible as a shooting star
  - Meteorite: a meteoroid surviving the burning process and impacting on Earth surface

  - Micro-meteoroids are small meteoroids, with diameter below a few mm, not detectable with ground observations methods. Natural particles have high velocities, up to 70 km/s with an average ~20 km/s:
    - from asteroids, prograde objects, with velocity ~10 to 40 km/s
    - from comets, they can be retrograde and reach velocity of 70 km/s

Micro-Meteoroids Environment

- LEO: micro-meteoroids are a minor part of the micro-particle environment
- GEO: micro-meteoroids are more likely to be encountered than space debris and for interplanetary missions, natural particles are the only hazard with respect to micro-particles
- Special attention must be paid to meteoroid showers, such as the Perseids and Leonids. These showers, which occur annually, can result in an increased risk for spacecraft by an increased meteoroid impact flux. Showers can be predicted, and action can be undertaken to minimize the impact risk
- Meteoroid showers occur when the Earth and an asteroid (or comet) orbit intersect. The Earth will enter the stream of the comet for a few days, and will be confronted with the individual particles
- Showers vary in strength, depending upon factors such as age, body composition, shower particle density and distribution and how close Earth approaches the shower core
- Meteoroid showers are named after a fixed point in the bkg star constellation. When a shower becomes visible due to burn-up in Earth atmosphere, the trails seem to originate from one fixed point, the radiant

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Name	Event maximum
Quadrantids	3 and 4 January
April Lyrids	21 and 22 April
Eta aquarids	3 and 4 May
Delta Aquarids	28 and 29 July
Alpha capricornians	29 and 30 July
Perseids	12 and 13 August
Orionids	21 and 22 October
Taurids	3 and 4 November
Leonids	16 and 17 November
Geminids	13 and 14 December
Ursids	21 and 22 December

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Micro-Particle Effect

- The micro-meteoroid and space debris environment are considered together: fast moving pieces of matter. Behaving like projectiles, they can penetrate material. Their energy is very high and the impact can vaporise the primary particle, generate fragments and leaving craters or holes on surfaces
- The amount of damage depends on the mass of the particle and the relative velocity of the impact. Many small impacts are observed on the surfaces returned from LDEF (Long Duration Exposure Facility), EURECA, HST Solar Array
- Man-made space debris and natural micro-meteoroid particles can damage satellites and constitute a serious hazard to manned spaceflight. The ISS, with its large surface area and long planned lifetime, has multi-wall design to protect it
- Environment models for impact risk assessment: Kessler NASA/JSC for space debris, Gruen for micro-meteoroids. Sophisticated micro-particle prediction models: NASA orbital debris engineering model ORDEM2000, ESA Meteoroid and Space Debris Terrestrial Reference MASTER-2005

Micro-Particle Analysis

- Evaluating space debris and micro-meteoroid effects:
  - Knowledge of size, velocity of particle penetrating a given shield design. The shield may comprise a single aluminium wall or multiple walls with spacing
  - Design equations give the particle size which just penetrates (or causes some defined damage) as a function of particle velocity for a given shield. The design equation can be used together with the environment model, providing particle fluxes as a function of size and velocity, to predict penetration or damage probability over a certain time
  - Good test results as a prerequisite to a reliable analysis
  - Since current technology impact tests cannot reach the extreme velocities of the debris population, hydrodynamic computer codes need to be used to augment the test data in establishing design equations
  - S/C geometry and orientation need to be taken into account because of the relative velocity of the S/C through the environment: new impact risk assessment tool (ESABASE2/Debris). It computes the number of impacts over time and failures for user-defined mission parameters, geometry, attitude and shield design
  - The environment remains uncertain, especially for particle sizes just below the trackability limit. More flight data are required

Atomic Oxygen

- In low Earth orbits, satellites encounter the very low density residual atmosphere composed primarily of oxygen in an atomic state. Although oxigen density is low, the flux is high
- Effects
  - The large flux of atomic oxygen, in a highly reactive state, can produce serious erosion of surfaces through oxidation. Thermal cycling of surfaces can remove the oxidised layer from the surface. Some surfaces respond differently by changing dramatically their surface structure and therefore properties, which are important for S/C thermal control
- Analysis
  - The flux of atomic oxygen depends on its density, the relative S/C velocity and the orientation of surfaces. The recession rate is proportional to the fluence (time-integrated flux) and is material dependent. Kapton recedes at about 3 μm per 10^{20} atoms/cm^2: a surface in LEO can accumulate 10^{21} atoms/cm^2 in a months. Preliminary predictions for the ISS indicated that Kapton exposed on ram surfaces could recede at 360 μm / solar cycle

Atomic Oxygen Analysis

- Atomic oxygen fluence analysis (ESABASE/Atomox)
  - Orbit (position, velocity), an orbit generator and mission evolution
  - Surface orientation with respect to velocity vector
  - Atomic oxygen density: MSIS-86 (known as CIRA-86) atmospheric model of Hedin et al. used to derive density as a function of altitude, time, solar and geomagnetic activity, latitude and longitude
  - Solar activity prediction (or observation)
- The worst-case fluence is to a ram surface and is greatest at solar maximum when the atmosphere expands
- Since atomic oxygen density varies strongly with altitude, strong variations are also expected in its effects. In a decaying satellite orbit most of the damage is caused towards the end of the mission
- Anti-sun-pointing surfaces in circular, low-inclination, low Earth orbits accumulate more atomic oxygen than sun-pointing ones (peak atomic oxygen density is after noon)
- Ground-test facilities are needed to be compared with model predictions. There is also a need for more flight data to evaluate long-term effects (LDEF)

Contamination

- Contamination from outgassing, venting, leaks and thruster firing can degrade surfaces on which contaminants deposit. The contaminant cloud can also disrupt payload operations (e.g telescopes). On-orbit contamination may modify surfaces and invalidate ground-based characterisation (charging properties measurements). High contaminant levels may also contribute to the onset of electrostatic discharge
- Analysis
  - ESABASE/Outgassing has been developed to compute deposition on surfaces of a 3-dim model of a S/C resulting from the outgassing of other surfaces
  - Direct flux, flux reflected by other surfaces, reflections from other contaminant molecules (using a simplified cloud model), and ambient gas scattering are taken into account
  - A temperature-dependent residence-time model is used for the outgassing

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