Space Environment Summary

Gravity field

The gravity field of Earth can be represented by the gravitational potential $U(r, \delta, \lambda)$ which is generally expressed by a harmonic expansion. [Eqs. 3.5, 3.6, 3.7] This expansion is a function of the distance from Earth's center of mass r, the latitude δ and the longitude λ. Each term of the expansion represents the deviation from the gravity field of a perfectly spherical Earth, described by the scaling coefficient $J_{n,m}$ and the orientation coefficient $\lambda_{n,m}$. The Legendre polynomials describe in what way the gravity field is altered by these coefficients.

A distinction is made between zonal ($J_{n,0}$), sectoral ($J_{n,n}$) and tesseral ($J_{n,m}$) terms where m is respectively $m = 0$, $m = n$ and $0 < m < n$. The way these irregularities are distributed on the surface of Earth can be seen in [Fig. 3.2].

The most important J-term is $J_{2,0}$ which is related to the ellipsoidal shape of Earth. $J_{2,0}$ causes nodal drift which can be used in our advantage: certain orbits have a drift which is exactly equal to the angular velocity of Earth around the Sun - so-called sun-synchronous orbits. These are often applied for Earth-observation missions.

The acceleration due to the gravity field of Earth in a certain direction can be found by taking the partial derivative of the gravitational potential. For the x-direction:

$$\ddot{x} = -\frac{\partial U}{\partial x} \tag{1}$$

Radial (r-)direction:

$$\ddot{r} = -\frac{\partial U}{\partial r} \tag{2}$$

North-South direction:

$$a_{nz} = -\frac{1}{r}\frac{\partial U}{\partial \delta} \tag{3}$$

East-West direction:

$$a_{ow} = -\frac{1}{r\cos\delta}\frac{\partial U}{\partial \lambda} \tag{4}$$

Atmosphere

Apart from orbital perturbations caused by the gravity field, atmospheric drag has an important effect on a satellites orbit. Since the atmospheric density decreases approximately exponentially with altitude this effect is strongly related to the altitude of an orbiting satellite. The density also changes as solar activity changes (stronger solar activity can result in 10 times higher density at high altitudes).

The drag experienced by a satellite is described by the following relation:

$$\bar{D} = -C_D \frac{1}{2}\rho V^2 S \frac{\bar{V}}{V} \tag{5}$$

where $\bar{D}$ is the drag vector, C_D is the satellites drag coefficient, V is the velocity with respect to the atmosphere and S is the surface area of the satellite normal to the velocity vector. This drag decreases the orbital energy of the spacecraft which is described by:

$$E = -\frac{\mu}{2a} \tag{6}$$

of which the kinetic energy is a part:

$$E_k = \frac{1}{2}\frac{m}{\sqrt{1-\frac{v^2}{c^2}}}v^2 \tag{7}$$

In the previous equations μ was the gravitational constant MG, a was the semi-major axis, m was the satellite mass, v was the velocity and c was the speed of light.

The composition of the atmosphere also changes with altitude. The partial pressure of a component i at altitude z is given by:

$$p_i(z) = \int_z^\infty \rho_i(h)g(h)dh \tag{8}$$

and the ideal gas law for component i holds:

$$p_i = \rho_i \frac{R}{M_i}T = n_i \frac{R}{N_A}T \tag{9}$$

with R the gas constant, M_i the molecular mass of the component, T the temperature and N_A Avogadro's number. The composition of the atmosphere can have strong effects on satellites, for example atomic oxygen can cause corrosion.

Foreign objects

Satellites are not alone in their orbits: they are accompanied by a lot of foreign objects. These can be either natural (micrometeoroids) or artificial (space debris). Space debris comes from man-made satellite missions, in many forms (satellites, stage remains, collision left-overs) and is in orbit. Therefore it also experiences orbit decay due to the atmosphere so especially debris in low orbits stays there for a limited amount of time. Since the atmospheric density is related to solar activity, so is the presence of space debris.

Micrometeoroids, on the other hand, have an extraterrestrial origin and are generally not in orbit around Earth but around the Sun (they just happen to cross the path of Earth). These come in many different shapes and sizes, but the smallest are most abundant. Micrometeoroids can have much larger velocities (and therefore kinetic energies) than space debris.

Three strategies are implemented against foreign objects: avoidance (dodge collisions or choose safe orbits), protection (armor your satellite) and prevention (make sure your satellite does not contribute to the collection of foreign objects). Still, the amount of space debris increases every year.

Radiation

Space is an excellent transmitter of radiation, and since convection and conduction between the satellite and the outside world are not available it is the only way that a satellites temperature is determined. Everything that has a temperature emits thermal energy:

$$Q_{out} = \epsilon A_{out} \sigma T^4 \tag{10}$$

where ϵ is the emissivity factor, A_{out} is the radiating area, σ is the Stefan-Boltzmann constant and T is the temperature. This is related to the change in temperature of that object:

$$mc_p \frac{dT}{dt} = Q_{in} - Q_{out} + Q_{intern} \tag{11}$$

where c_p is the heat coefficient, Q_{in} is the received radiation and Q_{intern} is the internally generated heat. The emitted energy can also be described as follows:

$$E_{tot} = \int_0^\infty E(\lambda) d\lambda = \sigma T_{gb}^4 \tag{12}$$

where T_{gb} is the grey-body temperature of the radiating object.

In the electromagnetic spectrum several types of radiation are discerned based on their frequency/wavelength (which are directly related: $\lambda = c/f$): gamma and röntgen radiation, ultraviolet radiation, visible light, infrared radiation and radio waves. The amount of radiation of a certain type emitted by a radiator can tell something about the radiator: a line spectrum (one wavelength emitted) is generated by atomic gasses, a band spectrum (collection of lines) is generated by molecular gasses and a continuous spectrum is generated by high temperature fluids and gasses and by solids.

Satellites receive radiation from several sources: solar radiation, albedo radiation (reflected solar radiation) and thermal radiation from other sources (generally Earth). This radiation can be used for attitude determination (e.g. star sensors) and for energy supply (solar panels). However, especially radiation can also cause damage either directly (for short-wavelength radiation) or through thermal effects. The radiation even causes orbit perturbations since photons have a mass, and thus, momentum:

$$p_{Sun} = \frac{E_{Sun}}{c} \tag{13}$$

where p_{Sun} is the pressure, E_{Sun} is the energy intensity and c is the speed of light.

Finally, the Sun also emits high energy particles known as particle radiation. This is strongly related to solar activity and is effected by the Earth magnetic field. This radiation has a lot of energy and can cause serious damage. An outburst of particle radiation is known as a Solar Particle Event (SPE).

Magnetic field

The Earth magnetic field is something that can have a strong influence on satellite missions, yet it is not fully understood. It is thought that the field is generated by currents in the rotating outer core which consists of fluid metals. Yet how this works exactly is not known, nor is it understood why the symmetry axis does not cross the geometric center of Earth, or why the polarity has changed repeatedly. Like the gravity model, the magnetic field is modeled as a harmonic expansion function $V(r, \Phi, \Lambda)$ [Eq. 7.15]. From this the radial component of the magnetic field strength can be found:

$$B_r = -Z = -\frac{\partial V}{\partial r} \tag{14}$$

and so can the tangential component:

$$B_\Phi = H = -\frac{1}{r}\frac{\partial V}{\partial \Phi} \tag{15}$$

which can be combined to find the total magnetic field strength:

$$B^2 = H^2 + Z^2 \tag{16}$$

or the differential equation for magnetic field lines:

$$\frac{rd\Phi}{dr} = \frac{H}{Z} \tag{17}$$

or, they can be used to find the Lorentz force on a charged particle:

$$\bar{F}_L = q\bar{v} \times \bar{B} \tag{18}$$

where q represents the charge of the particle and $\bar{v}$ the velocity vector. Inspecting this Lorentz force relation, it can be found that if the particle has a velocity component normal to the magnetic field lines v_n, this results in a circular motion. The Larmor radius r_L of this motion can be found to be:

$$r_L = \frac{mv_n^2}{F_{cent,L}} = \frac{mv_n}{qB} \tag{19}$$

and therefore the rotational velocity ω is:

$$\omega = \frac{v_n}{r_L} \tag{20}$$

and the rotational period T and frequency f:

$$T = \frac{1}{f} = \frac{2\pi}{\omega} \tag{21}$$

This circular motion is known as the cyclotron motion. The particles also experience a motion due to the increase of the magnetic field strength towards the poles: the bounce motion. This causes the particles to move from North to South and back. These motions cause particles to be trapped in specific regions, the Van Allen Belts. Finally, the particles also experience a drift motion due to external forces (e.g. gravitational pull) which results in movement in East-West direction.

The magnetic field of Earth can affect satellites as well. If a satellite generates a magnetic field a torque results (this can also be used as a means of attitude control), and if a satellite is charged it experiences a Lorentz force just like the previously mentioned particles. Since the magnetic field affects satellites, satellites can also be used to study the magnetic field.

The Van Allen Belts pose their own set of challenges for a satellite: the high-energy charged particles can cause Single Event Upsets (SEUs) when they interfere with electric equipment. The problems caused by SEUs are similar to the ones caused by Solar Particle Events.

Magnetosphere

The magnetic field of Earth is perturbed by particle radiation from the Sun and the Suns magnetic field. The particles radiated by the sun arrive at Earths magnetic field at extremely high velocities, which can be said to be in the hypersonic flow regime. Therefore the geometry of the magnetosphere is very similar to situations in hypersonic aerodynamics, most notably the fact that the magnetic field only has an influence up to a certain bow shock after which its effects cannot be noticed. [Fig. 8.1]

This bow shock is located at 15 Earth radii in the direction of the sun and forms the boundary between unperturbed and perturbed solar plasma flow. The particles found behind the bow shock are still mostly interplanetary. The boundary between the regions of interplanetary and Earth particles is called the magnetopause. It is located at a distance of 7 to 10 Earth radii in the direction of the Sun.

Due to the dipole character of the Earth magnetic field, at the poles cusps can be found where interplanetary particles can enter the Earth atmosphere without much disruption. This affects the atmosphere, causing *aurora borealis* and *aurora australis* at, respectively, the north and south poles.

On the night side of Earth, the magnetic field can much more freely propagate. It does so up to distances of more than 1000 Earth radii. The magnetic field lines propagate in parallel, separated by the neutral sheet which is located between the two plasma sheets. The exact characteristics of the magnetic field in this region are poorly understood.

Finally, the plasmasphere is distinguished. This is a region where the magnetic field of Earth does not rotate as it does everywhere else but is fixed with respect to the sun. The magnetosphere has been the subject of several satellite missions.

Vacuum

One last important characteristic of the space environment is the extreme vacuum that is present. This can cause sublimation which might result in weaker materials, cold welding and constraints on lubricants which can be used. In fact, the deposition of these sublimed materials on other parts of the spacecraft (lenses, mechanical systems, electric circuits) might also cause problems. The vacuum is also the cause that convection and conduction between the spacecraft and environment do not take place.