Developing an Elective Course on Satellite Communications in Undergraduate Electrical Engineering Curriculum

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Abstract

This paper presents backgrounds for developing an unconventional elective course on satellite communications in undergraduate electrical engineering curriculum at Saint Louis University to cope with the changing discipline boundaries, and provides a short and concise treatment of materials that are unconventional to electrical engineering discipline. The explosive growth of communications satellites and the perceived potential of the medium for novel applications have generated intense interests in both the government and private sectors. The satellite communications engineering is the outcome of such diverse topics as orbital mechanics, electromagnetic fields and waves, radio electronics, and communication theory. This course is an attempt to include materials from these areas useful to understand the overall concepts of satellite communications. Mathematical rigors and complexities are purposely avoided in many cases to make it more enjoyable and at the same time comprehensible to students. It provides a broad coverage of topics, in some cases very briefly, as practical as possible. Despite the integration of rather many unconventional topics falling beyond the discipline boundaries, electrical engineering seniors find the course very exciting and challenging.

Keywords: Antenna look angles, attitude control, eclipse, equinox.

1.0 Introduction

For more than seven decades, Parks College of Engineering, Aviation and Technology, one of the 12 schools and colleges at Saint Louis University, has had the tradition of excellence in aerospace education. Founded in 1927 as the first federally certified college of aviation in the country, Parks College prepares graduates for exciting and rewarding careers in aerospace industry and other related technological fields.The explosive growth of communications satellites and the perceived potential of the medium for novel applications have generated intense interests in both the government and private sectors. This warrants a large demand for a course in satellite communications suitable for students majoring in any of the electrical, avionics and aerospace engineering disciplines offered at Saint Louis University. This course is an attempt to include materials from those areas useful to understand the overall concepts of satellite communications. It provides a broad coverage of topics, in some cases very briefly, as practical as possible. It is based on the assumptions that students have completed the usual undergraduate courses in mathematics and physics to understand the concepts of orbital mechanics and electromagnetic fields.

A minimum of basic electrical engineering that includes materials in electronics and circuit theory is required. Handouts are provided to some students lacking backgrounds in communications theory and electromagnetic radiation. Many related topics that are not covered in previous courses are presented following the "just-in" approach. From the techniques of orbital aspects and radio wave propagations to the design of communication links, the course treats the entire field of satellite communications

A communications satellite is a very simple concept, but simple concepts sometimes change the entire fabrics of the society. Terrestrial communications face long distance constraints of requiring a physical path between terminals. A communications satellite, in essence, is a radio relay in the sky. Satellite communications engineering combines such diverse topics as orbital mechanics, satellite construction including various sub-systems, launching and positioning of geostationary satellites, geometric considerations of satellite, space environments and its effects, radio wave propagation, and space link and satellite access. This paper focuses briefly on unconventional topics falling beyond the discipline boundaries. Mathematical rigors and complexities are purposely avoided in many cases to make it more enjoyable and at the same time comprehensible to students.

2.0 Orbital Aspects of Geostationary Satellite Communications

This section examines various topics related to orbital aspects of a geostationary satellite that will lead to provide several important practical results such as locating the satellite in the orbit, look angle determination, and orbital effects in communication system performance including eclipses and solar interferences. It is the first treatment of the subject for electrical engineering students that covers Kepler's laws of planetary motion to antenna look angles

2.1 Location of Satellite in the Orbit

Satellites orbiting around the earth follow the same laws that govern the motion of the planets around the sun. Kepler's laws govern the planetary motion and apply quite generally to any bodies in space which interact through gravitation. The more massive of the two bodies is referred to as the primary, the other, the secondary. Kepler's laws are stated as follows:

- The orbit of the satellite describes an ellipse with the primary at one focus.
- For equal time intervals, a satellite sweeps out equal areas in its orbital plane, focused at the primary.
- The square of the periodic time of the orbit is proportional to the cube of its semi-major axis.

The orbit of a satellite in its orbital plane is described in polar coordinates by the equation:

$$r_0 = \frac{a(1-e^2)}{1+e\cos\phi_0} \qquad (1)$$

whereφ_0 is the true anomaly and specifies the position of the satellite on the orbit, a is the semi-major axis, and e is the eccentricity. The true anomaly φ_0 is an average value of the angular position of the satellite with reference to the perigee (closest point on the orbit from earth). The orbit of the satellite on orbital plane is shown in Figure 1.

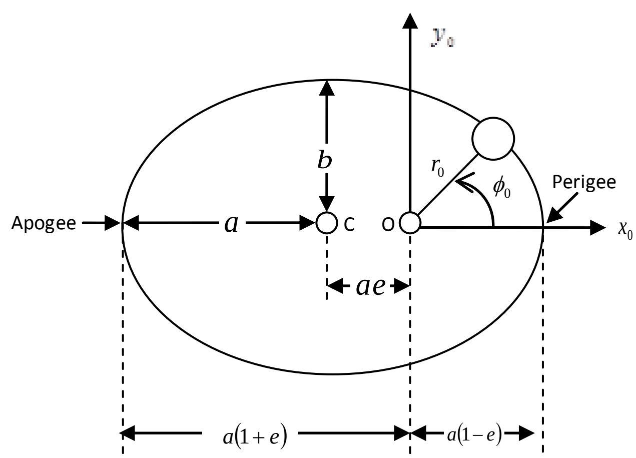

Figure1. The Orbit of the Satellite in the Orbital Plane

2.2 Antenna Look Angles

The antenna look angles for an earth station antenna are the azimuth and elevation angles required so that it points directly at the geostationary satellite. The azimuth angle is the angle by which the antenna must be rotated clockwise around its local vertical from the geographic north. The azimuth angle A is obtained from Table 1, by determining the angle α from the following formula:

$$\alpha = \arctan(\tan L / \sin \ell) \qquad (2)$$

where ℓ is the earth station latitude , and L is the absolute difference between the satellite (SL) longitude and that of the earth station (ES).

Table1. Calculating Azimuth

Hemisphere	SL east of ES	SL west of ES
North Hemisphere	$A = 180^0 - \alpha$	$A = 180^0 + \alpha$
South hemisphere	$A = \alpha$	$A = 360^0 - \alpha$

Elevation angle is the angle measured upward from the horizontal plane, and is determined from the following formula:

$$E = \arctan[(\cos\phi - R_e/(R_e + R_0))/(1-\cos^2\phi)^{1/2}] \quad (3)$$

where $\cos\phi = \cos\ell \cos L$, R_e is the radius of earth (6378 km), and R_0 is the satellite altitude (35786 km).

2.3. Earth Eclipse of Satellite

If the earth's equatorial plane coincided with the ecliptic plane, geostationary satellites would be eclipsed by the earth once each day. But the equatorial plane is tilted 23.4^0 to the ecliptic plane, and this keeps the satellite in full view of the sun for most days of the year. Eclipses occur during two periods that begin 23 days before the equinox and 23 days after the equinox [1]. The eclipses last about 10 minutes at the beginning and end of the eclipse period and increases to a maximum duration of about 72 minutes at full eclipse. During the eclipse the solar cells do not function, and the operating power must be supplied entirely from storage batteries. This can reduce the available power significantly as the satellite nears the end of its life, and it may necessitate shutting down some of the transponders. Satellite designers must guard against harmful transients as solar power fluctuates sharply at the beginning and end of an eclipse.

2.4. Sun Transit Outage

Another event which must be allowed for during the equinoxes is when the sun passes through the beam of the ES antenna. When this happens the sun appears as an extremely noisy source which completely blanks out the signal from the satellite. This effect is known as the sun transit outage, and it lasts for very short periods each day for about 6 days around the equinoxes. A receiving ES can do nothing about except wait for the sun to move out of the main lobe of the antenna. It always occurs during the daytime, and it forces many users to arrange alternative channels.

2.5. Launching and Positioning of Satellite

The procedure of launching satellites is based on the well-known*Hohmann transfer* which allows the satellite to be transferred from a circular earth orbit to another at different altitudes in the same plane with minimum energy consumption, despite the satellite, at least theoretically, could be placed into the geosynchronous orbit in one operation. The Hohmann Transfer orbit is a result of practical considerations of cost and launch vehicle capability, which dictates a three-step process [2], as depicted in Figure 2.

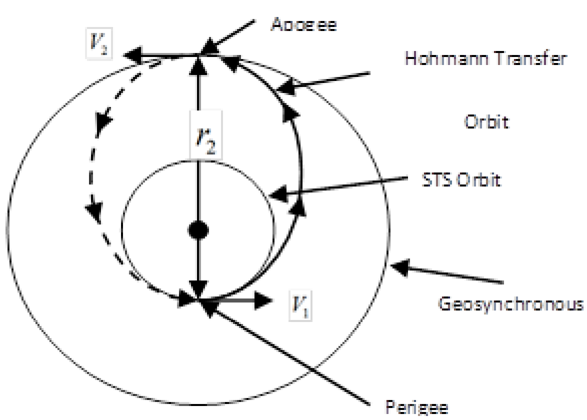

Figure 2. The Steps in Launching Communications Satellite

The Hohmann elliptical orbit is tangent to the circular low earth orbit (LEO) at perigee and to the geostationary satellite orbit (GEO) at apogee (furthest point from the earth). At the perigee, in case of rocket launch, the rocket injects the satellite with the required thrust into the transfer orbit. With Space Transportation System (STS), the satellite must carry a perigee kick motor (PKM) which imparts the required thrust at the perigee. At apogee, the apogee kick motor (AKM) changes the velocity of the satellite to place into a circular orbit in the same plane. It takes about 1 to 2 months for the satellite to be fully operational. Throughout the launch and acquisition phases, a network of ground station, spread across the earth, is required to perform the tracking, telemetry and command functions.

3.0 Space Environment and Its Effects

This section focuses on the main environmental factors which dictate the design and operation of the satellite on its orbit during its lifetime. There are many factors that affect the operation of satellite in space environment. These include gravitational fields due to earth, space vacuum, space radiation, earth's magnetic field, and meteoroids and space debris. The geostationary satellite is subject to perturbations which cause it drift away from the nominal position and which create attitude perturbing torques.

3.1 Earth's Gravitational Field

The gravitational field due to earth is the main external source that affects an earth orbiting satellite. It is not uniformly spherical as a result of the non-homogeneous distribution of the mass of the earth, and its potential is represented by an expansion in Legendre polynomials J_n in ascending powers of (earth's radius R_e/orbital radius R_0) [3]. Since R_e/R_0 is very small, we can ignore higher order terms and write the related potential function as follows:

$$U = \frac{\mu}{R_0}[1+(\frac{R_e}{R_0})^2\{-J_2 + 3J_{22}\cos 2(L-L_{22})\}] \qquad (4)$$

whereμ is the earth's gravitational constant, L is the longitude of the satellite measured from the Greenwich meridian, and $L_{22} = 15^0$ west.

The torque resulting from the earth's gravitational field may cause the satellite to rotate about its center of mass unless the axis of smaller inertia of the satellite is aligned with the earth local vertical. Assuming the z-axis to be of revolution for the satellite, the corresponding torque is given by:

$$T_g = 3\frac{\mu}{r^3}(I_z - I_x) \qquad (5)$$

where μ is the earth gravitational field as in (1), r is the distance from the satellite to the center of the earth, $I_z$is the moment of inertia about the z-axis, I_x is the moment of inertia about any axis perpendicular to the z-axis, and θ is the angular deviation between the z-axis and the perpendicular to orbital plane.

3.2 High Vacuum

High vacuum is one of the dominant factors in space environment. The mechanical properties of most material change in high vacuum of space. Some metals such as steel and molybdenum have improved creep and fatigue properties because no gases are absorbed by the metal. Aluminum and magnesium have poorer properties, partly because their surface is not oxidized which hardens the metal surface. As the altitude increases, the density of particles diminishes very rapidly. The effect of aerodynamic drag is considered insignificant at a very high altitude. The high vacuum space acts as a good electrical insulator. Electrical surfaces can be closely spaced. On the other hand, there is a danger of sublimation depositing metallic layers on insulating surfaces.

3.3 Thermal Radiation

A classic account of the thermal radiation is provided in [4]. Thermal radiation depends on its temperature T and its emitance ε. The Stefan Boltzmann's law expresses the radiated flux leaving an element of surface of the body as:

$$M = \varepsilon\sigma T^2 \qquad (6)$$

where $\sigma = 5.67 \times 10^{-8}$ W-m $^{-2}$ K $^{-4}$.

The Plunk radiation law expresses mathematically the spectral radiance of a black body per unit wavelength as:

$$L_\lambda = C_{1L}\lambda^{-5}((C_2/\lambda T)-1)^{-1} \qquad (7)$$

whereC_{1L} = 1.19 x 10^{-16} W m^2/sr, C_2 = 1.439 x 10^{-2} mK.

A functional form of the Planck law, known as the Wein law, relates the wavelength at which maximum spectral radiance L_m of a blackbody occurs to its temperature T:

$$\lambda_m T = b_1 \qquad (8)$$

$$L_m / T^5 = b_2 \qquad (9)$$

whereb_1 = 2.9 x 10^{-3} mK, and b_2 = 4.1 x 10^{-3} W $m^{-3}K^{-5}sr^{-1}$

Space behaves like a blackbody at approximately 5 K with absorbency equal to 1. Thus all thermal energy radiated is completely absorbed. The radiation received by an earth orbiting satellite originates from the sun and the earth.

3.4 Solar Radiation

The radiation from the sun enables the satellite to generate its required electricity. However, it also has harmful effects. Almost half of its electromagnetic radiation is in the form of x-rays and γ-rays causing occasional disintegration of nuclei and causing ionization of matters. In addition to electromagnetic radiation, satellites are bombarded by radiation in the form of high energy particles. The satellite passes through enormous radiation belts consisting of electrons trapped by the earth's magnetic field resulting in degradation the performance of the solar cells. A satellite is launched with somewhat more power output than it needs to compensate the solar cell degradation.

3.5 Meteoroids and Space Debris

The earth is surrounded by a cloud of meteorites and debris, the density of which decreases as the altitude increases. Most of the debris consists of tiny particles which can penetrate 2 millimeters of aluminum. A meteorite is a piece of space debris large enough to penetrate the earth's atmosphere and land on the earth. Large meteoroids are extremely unlikely to hit a relatively small satellite, and the satellite can survive the impact of small ones. During the lifetime of a communication satellite it will suffer a little surface erosion and a few pin pricks, but it will be very unlikely to be hit by meteoroids of the size of rifle bullets. The momentum transmitted to a satellite by a meteorite collision is best evaluated statistically. Impacts between meteorites and satellites may be assumed to occur at random and the Poisson distribution may be applied, thus the probability of n impacts in the mass ranges M_2—M_1occurring over an S in time t may be summarized as:

$$P(n) = \frac{(Sft)^n \exp(-Sft)}{n!} \qquad (10)$$

where$f$ is the particle flux in the mass range M_2—$M_{1,}S$ is the exposed area, and t is the time of exposure.

4.0 Geostationary Satellite Construction

A geostationary satellite is designed such that it can survive the hostile environment of outer space for the expected lifetime. In order to support the communications system, the satellite must provide a stable platform on which to mount the antennas, be capable of station keeping, provide the required electrical power for communication system, and also provide a controlled-temperature environment for the communications electronics. A geostationary communication satellite can be divided into subsystems each of which has a specific function. It is common practice to distinguish the *payload* that performs the primary mission, from the *bus* which includes all other subsystems and is designed to support the communication subsystems. This section discusses the subsystems needed, particularly the unconventional ones to electrical engineering students, on a spacecraft to support its primary mission of communications. Those who are interested in satellite design should refer to the literature of the field.

4.1 Attitude and Orbit Control Subsystem (AOCS)

The attitude of a satellite refers to its orientation in space. Control of the attitude of a satellite is necessary so that the antennas, which often have narrow beam, are pointed correctly at the earth. A number of forces, referred to as disturbing torques, can alter the attitude, some examples being the gravitational fields due the earth and the moon, solar radiation, and the meteorite impacts as discussed in the previous section. Because the satellite moves round the earth's center in its orbit, the forces described above all vary cyclically through 24-hour period. This tends to set up a *nutation* of the satellite, which must be damped mechanically. Usually, the attitude control process takes place abroad the satellite based on the attitude data obtained from the sensors. Where a shift in attitude is desired, an attitude maneuver is executed. The control signal needed to achieve this maneuver may be transmitted from the ES.

Once the attitude of the satellite is detected, attitude corrections can be initiated. The torque generating devices consists of momentum devices, thrusters, and magnetic coils.

Varying the speed of rotation ω of a wheel with a moment of inertia I, one can alter the kinetic momentum $H=I\omega$ of the wheel and induce a correcting torque T given by:

$$T = \frac{dH}{dt} = I\frac{dy}{dt} \quad (11)$$

Thrusters produce forces by expelling material through nozzles. The thrust F is related to the expelled material mass per unit dm/dt, and depends on the specific impulse I_{sp} of the expelled material as follows:

$$F = gI_{sp}\frac{dm}{dt} \quad (12)$$

where$g$ is the gravitational acceleration at the earth's surface.

Magnetic coils create a magnetic moment M when driven by an electrical current I. The interaction of the coil's magnetic momentum M with the earth's magnetic field B generates the desired torque expressed as $\boldsymbol{T} = \boldsymbol{M} \times \boldsymbol{B}$.

4.2 Telemetry, Tracking, and Command (TT&C) Subsystem

The telemetry, tracking, and command subsystem is essential to the successful operation of a communication satellite. It is a part of the satellite management task, which also involves an ES, usually dedicated to the task. The main functions of the satellite management are to control the orbit and the attitude of the satellite, monitor the status of all sensors and subsystems on the satellite, and switch on or off sections of the communication system. Tracking is performed primarily by the ES.

Telemetry and command may be thought of as complementary functions. The telemetry subsystem transmits information about the satellite to the ES, while the command subsystem receives command signals from the ES. The command subsystem demodulates and, if necessary, decodes the command signals and routes these to the appropriate equipment needed to execute the necessary action. To maintain security, the command signals are often encrypted.

Tracking of the satellite is accomplished by a number of techniques. Velocity and acceleration sensors on the satellite can be used to establish the change in the orbit from the last known position, by integration of the data. The ES controlling the satellite can observe the Doppler shift of the telemetry carrier to determine the rate at which the range is changing. Together with accurate angular measurements from the ES antenna, range is used to determine the orbital elements. With precision equipment at the ESs, the position of the satellite can be determined within an acceptable value.

4.3 Antenna Subsystem

The antennas carried abroad a satellite provide the dual functions of receiving the uplink and transmitting the downlink signals. They range from dipole antennas where omnidirectional characteristics are required to the highly directional antennas required for telecommunications purposes. Directional beams are usually produced by means of reflector-type antenna, usually the paraboloidal reflector. The antenna of a communications satellite is often a limiting element in the complete system. Ideally, there should be one antenna beam for each earth station, completely separated from all other beams, for transmit and receive. A compromise between one beam per station and one beam for all stations has been used in many satellites by using zone-coverage beams and orthogonal polarization within the same beam to provide more channels per satellite. Frequency reuse with spot beams and multi-beam satellite system allow for an increase of the system capacity. Frequency reuse is achieved either by *spatial separation* of the beams, that is beams at same frequency covering different parts of the earth, or by *polarization discrimination*, that is two beams at the same frequency but with orthogonal polarization covering same part of the earth.

4.4 Transponder Subsystem

Transponder subsystem is the major component of a communication satellite, and is an electronic assembly which forms a single communications channel between the receive and transmit antennas. Basically, it amplifies the signal from an input power in the order – 100 dBW to an output power of about 10 dBW, and then performs the frequency down conversion which avoids interference between the powerful transmitted signal and the incoming weak signal.

4.5 Electric Power Subsystem

All communications satellites derive their electrical power from *solar cells* which work on the principle of photovoltaic effect. Silicon is the most widely used material in solar cells that are relatively thick mono-crystalline chip. Work is in progress to produce ultra-thin low mass cell.

Other research aims at replacing silicon with more efficient materials. In order to maintain service during an eclipse, storage batteries must be provided. Until recently, nickel-cadmium batteries have been used. Nickel-hydrogen [5] batteries are used in the Hughes HS 601 and were first introduced into the Intelsat series. Research is underway on silver-hydrogen batteries.

5.0 Conclusion

Although electrical engineers may be interested primarily in one area, they must be competent and knowledgeable in other related areas to interact in order to become more productive and efficient. The interaction with other disciplines is a part of what makes electrical engineering a challenging and exciting profession. The explosive growth of communications satellites and the perceived potential of the medium for novel applications have generated intense interests in both the government and private sectors. This warrants a large demand for a course in satellite communications suitable for students majoring in any of the electrical, avionics and aerospace engineering disciplines offered at Saint Louis University. The satellite communications engineering is the outcome of such diverse topics as orbital mechanics, electromagnetic fields and waves, radio electronics, and communication theory. This paper focuses briefly on unconventional topics falling beyond the discipline boundaries rather than a comprehensive treatment of the subject. Mathematical rigors and complexities are purposely avoided in many cases to make it more enjoyable and at the same time comprehensible to students. Mathematical descriptions that are used in this paper are mostly independent and incoherent from each other due to the diverse nature of the topics. The topics—earth space communication link design to achieve required carrier-to-noise ratio for analog and digital modulation links, modulation techniques used in satellite communications systems, propagation problems caused by rain attenuation on earth-space links, multiple-access techniques such as FDMA, TDMA and CDMA—forming the integral parts of the course are purposely avoided in order to primarily focus on the topics falling beyond discipline boundaries.

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