Contemporary Engineering Themes B –

Satellite and GNSS systems

Assessment

PART1 Answer ALL Questions

Design a satellite communication link operating in the Ku band to meet C/N and link margin specifications.

a) UPLINK: Design a transmitting earth station (transmitted antenna gain in dB and earth station transmitted power in W) to provide $(C/N)_{up}$ of 35 dB in a Ku-band transponder. Use an uplink antenna with a diameter of 3m and an aperture efficiency of 65%. The uplink station is located at -2 dB contour of the satellite footprint. Allow 1.5 dB for clear air atmospheric attenuation and other losses. Path length to satellite is 38 500 km. Assume standard frequency allocation of 14GHz for the uplink in Ku-band.

[25 marks]

For satellites, there exists the relationship of Equation 1. This equation is used to calculate the power received at the input of the transponder "P_r":

$$(\frac{C}{N})_{up,dB} = P_r - N_{tr}[dbW] \qquad \textbf{Eqn.1}$$

"$(C/N)_{up}$" is 35 dB. Equation 2 is the formula to calculate the noise power at the transponder input "N_{tr}". "k" is Boltzmann's constant in decibels, it is -228 dBW/K/H. Transponder bandwidth B_n is 36 MHz and the receive system noise temperature Ts is 500 K. "N_{tr}" can be calculated as:

$$N_{tr}[dBW] = 10\log(k) + 10\log(B_n) + 10\log(T_S) \qquad \textbf{Eqn.2}$$

$$N_{tr}[dBW] = -288.6 + 10\log(36 \times 10^6) + 10\log(500) = -126.05\ dBW$$

With the value of "N_{tr}" and "$(C/N)_{up}$", "P_r" can be calculated as:

$$P_r = (\frac{C}{N})_{up,dB} + N_{tr} = 35 - 126.05 = -91.05\ dBW$$

Equation 3 is the formula to calculate the transmitted antenna gain "G_t", diameter of the uplink antenna "D" is 3m, and its aperture efficiency "η_e" is 65%. The wavelength "λ" can be calculated by Equation 4, the speed of light "c" is 3×10^8 m/s and the standard frequency allocation for the uplink in Ku-band "f" is 14GHz. With these values, the magnitude of the wavelength "λ" can be calculated. Then the magnitude of "G_t" also can be calculated:

$$G_{t,dB} = 10\log\left(\eta_e \frac{4\pi}{\lambda^2} A\right) = 10\log\left(\eta_e \frac{4\pi}{\lambda^2}\frac{D^2\pi}{4}\right) = 10\log\left(\eta_e (\frac{D\pi}{\lambda})^2\right) \qquad \textbf{Eqn.3}$$

$$\lambda = \frac{c}{f} \qquad \textbf{Eqn.4}$$

$$\lambda = \frac{3 \times 10^8}{14 \times 10^9} = 0.021 \text{ m}$$

$$G_{t,dB} = 10 \log \left(65\%(\frac{3\pi}{\frac{3 \times 10^8}{14 \times 10^9}})^2 \right) = 50.99\ dB$$

Equation 5 is the formula that can calculate the earth station transmitted power "P_t". The power received at the input of the transponder "P_r" is -91.05 dBW, the transmitted antenna gain "G_t" is 51.01 dBW, the Antenna gain "G_r" is 25 dB. The uplink station is located at -2 dB contour of the satellite footprint, so the value of L_{ant} is 2 dB. There is an allowance of 1.5 dB for clear air atmospheric attenuation and other losses, the value of L_{misc} is 1.5 dB. The path loss L_{path} can be calculated by Equation 6 and the path length to satellite "R" is 38 500 km. With these values, the magnitude of "L_{path}" can be calculated. Then the magnitude of "P_t" can be calculated:

$$P_{r,dB}[dbW] = P_t + G_t + G_r - L_{path} - L_{ant} - L_{misc} \qquad \textbf{Eqn.5}$$

$$P_t = P_{r,dB} - G_t - G_r + L_{path} + L_{ant} + L_{misc}$$

$$L_{path} = 20 \log \left(\frac{4\pi R}{\lambda}\right) = 20 \log \left(\frac{4\pi \times 38500 \times 10^3}{\frac{3 \times 10^8}{14 \times 10^9}} \right) = 207.07\ dB \qquad \textbf{Eqn.6}$$

$$P_t = -91.05 - 50.99 - 25 + 207.07 + 2 + 1.5 = 43.53\ dBW = 22542.39\ W$$

So, the transmitted antenna gain "G_t" is 50.99 dB and the earth station transmitted power "P_t" is 22542.39 W.

b) DOWNLINK: Find the power level of the earth station receiver and the antenna gain at the earth receiver station so that overall carrier to noise ratio is 15 dB. Miscellaneous downlink losses are 0.5dB. Earth station is located at -2dB contour of satellite transmitting antenna. The earth station receiver has the following noise temperatures: noise temperature of the input signal is 25K, noise temperature of the RF amplifier is 400K, noise temperature of the mixer is 450 K and the noise temperature of the IF amplifier is 550K. The gain of the RF amplifier is 35 dB, the gain of the mixer is 0dB and the gain of the IF amplifier is 20dB.
Assume standard frequency allocation of 11GHz for the downlink in Ku-band.

[25 marks]

Equation 7 shows the relationship between the overall C/N "$(C/N)_o$", up C/N "$(C/N)_{up}$"and down C/N "$(C/N)_{down}$". "$(C/N)_o$" is 15 dB, $(C/N)_{up}$ is 35 dB, so the value of "$(C/N)_{down}$" can be calculated as:

$$(\frac{C}{N})_o = \frac{1}{1/(C/N)_{up}+1/(C/N)_{down}} \qquad \textbf{Eqn.7}$$

$$(C/N)_{down} = \frac{(C/N)_{up} \times (C/N)_o}{(C/N)_{up} - (C/N)_o} = \frac{10^{3.5} \times 10^{1.5}}{10^{3.5} - 10^{1.5}} = \frac{3162.28 \times 31.62}{3162.28 - 31.62} = 31.93 = 15.04\ dB$$

Equation 8 can calculate the noise temperature of the system "T_{system}". Noise temperature of the input signal "T_{in}" is 25K, noise temperature of the RF amplifier "T_{RF}" is 400K, noise temperature of the mixer "T_m" is 450 K and the noise temperature of the IF amplifier "T_{IF}" is 550K. The gain of the RF amplifier "G_{RF}" is 35 dB, and the gain of the mixer "G_m" is 0dB.

$$T_{system} = T_{RF} + T_{in} + \frac{T_m}{G_{RF}} + \frac{T_{IF}}{(G_{RF}G_m)} \qquad \textbf{Eqn.8}$$

$$T_{system} = 400 + 25 + \frac{450}{10^{3.5}} + \frac{550}{10^{3.5} \times 10^0} = 425.32\ K$$

Equation 9 is the formula to calculate the electrical power "P_n". "k" is Boltzmann's constant in decibels, it is -228 dBW/K/H. Earth station receiver IF noise bandwidth "B" is 27 MHz and the system noise temperature "T_{system}" is 425.32 K. "P_n" can be calculated as:

$$P_n[dbW] = K + T + B \qquad \textbf{Eqn.9}$$

$$P_n[dbW] = -228.6 + 10\log(425.32) + 10\log(27 \times 10^6) = -128.00\ dBW$$

Equation 10 is the formula to calculate the power level of the earth station receiver "P_r". "$(C/N)_{down}$" is 15 dB and "P_n" is -128 dBW. "P_r" can be calculated as:

$$P_r = (C/N)_{down} + P_n \qquad \textbf{Eqn.10}$$

$$P_r = 15.04 - 128.00 = -112.96\ dBW$$

The standard frequency allocation for the downlink in Ku-band "f" is 11 GHz. Based on Equation 4, the waveform length is:

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{11 \times 10^9} = 0.03\ \mathrm{m}$$

The antenna gain at the earth receiver "G_r" can be calculated by Equation 5. The transponder saturated output power in Ku band "P_t" is 40 W, the power of the earth station receiver "P_r" is -113 dBW, the antenna gain "G_t" is 25 dB. Miscellaneous downlink losses "L_{misc}" are 0.5dB. Earth station is located at -2dB contour of satellite transmitting antenna, so the value of "L_{ant}" is 2 dB. The path loss L_{path} can be calculated by Equation 6 and the path length to satellite "R" is 38 500 km. With these values, the magnitude of "L_{path}" can be calculated. Then the magnitude of "G_r" can be calculated:

$$P_{r,dB}[dbW] = P_t + G_t + G_r - L_{path} - L_{ant} - L_{misc}$$

$$G_r = P_r - P_t - G_t + L_{path} + L_{ant} + L_{misc}$$

$$L_{path} = 20\log\left(\frac{4\pi R}{\lambda}\right) = 20\log\left(\frac{4\pi \times 38500 \times 10^3}{\frac{3 \times 10^8}{11 \times 10^9}}\right) = 204.98\ dB$$

$$G_r = -113.04 - 10\log(40) - 25 + 204.98 + 2 + 0.5 = 53.50\ dB$$

The power level of the earth station receiver "P_r" is -112.96 dBW and the antenna gain at the earth receiver station "G_r" is 53.50 dB.

Other specifications for the satellite and the earth receiver are:

Satellite parameters are:

Antenna gain 25 dB;

Receive system noise temperature 500 K;

Transponder saturated output power in Ku band 40 W;

Transponder bandwidth 36 MHz;

Signals: FM-TV analog signal.

Earth station receiver IF noise bandwidth is 27MHz.

Minimum C/N overall = 12 dB.

Perform your calculations using decibels.

(Boltzmann's constant in decibels is k=-228.6 dBW/K/Hz)

All numerical results to be rounded to the 2nd decimal place

PART2 Answer ALL Questions

For Q1 and Q2, you will work with your unique 8-digit student ID number to replace a variable. Be sure to clearly state your ID number and the calculated variable at the start of your solutions.

Take your ID number and sum the first and last digits together. Take this value to replace the variable K in Q1 and Q3. (e.g. if your ID were 30463117, the sum would be 3 + 7 = 10 =K).

1. a) A GPS signal is transmitted from an altitude of 20,000 km above the earth's surface. Calculate the path length assuming an elevation angle of (50 + ***K***) degrees.

Answer:

The Student ID number is 20320941, so the variable "K" can be calculated as:

$$K = 2 + 1 = 3$$

The degrees of the elevation angle "θ_{EL}" are:

$$\theta_{EL} = 50^{\circ} + 3^{\circ} = 53^{\circ}$$

The formula to calculate the path length "R" is:

$$R = \sqrt{{R_E}^2(\sin^2(\theta_{EL}) - 1){R_{sv}}^2} - R_E \sin(\theta_{EL}) \quad \textbf{Eqn.11}$$

In this formula, "R_E" is the radius of earth, the value of it is: 6371 Km. "R_{sv}" is the transmission path length, the value of it can be calculated as:

$$R_{sv} = \text{Altitude} + R_E \quad \textbf{Eqn.12}$$

$$R_{sv} = 200000 \times 10^3 + 6371 \times 10^3 = 26371\ Km$$

Therefore, the value of the path length "R" can be calculated as:

$$R = \sqrt{(6371 \times 10^3)^2(\sin^2(53^{\circ}) - 1) + (26371 \times 10^3)^2} - 6371 \times 10^3 \times \sin(53^{\circ})$$

$$R = 2.10 \times 10^7\ m$$

The value of path length "R" is 2.10×10^7m.

[4 marks]

b) How many GNSS satellites are required to achieve a navigation fix in 3 dimensions and why?

Answer:

To determine a three-dimensional navigation fix using GNSS, a minimum of four satellites are required.

This is because each GNSS satellite provides a distance measurement for the receiver. To determine the position of the receiver in three dimensions, the position of at least three spheres whose surfaces intersect, the X, Y and Z coordinate need to be determined. Ideally, this would be determined using three satellites. However, due to the difference in the accuracy of the receiver's clock and the satellite's clock, using only three would result in significant errors. The fourth satellite survey provides an additional measurement that helps to determine the precise position of the receiver in three-dimensional space and its clock deviation.

[4 marks]

c) What is the main difference between how CDMA is used in communication systems and GNSS systems?

Answer:

The main difference between the way CDMA is used in communications systems and GNSS systems is the use of CDMA codes.

In a communications system, CDMA codes are used to enable multiple users to share the same frequency band simultaneously for transmitting and receiving without interfering with each other. Each user is assigned a unique CDMA code to modulate their transmitted signal.

CDMA codes can be used in GNSS systems to achieve accurate range measurements. Each GNSS satellite transmits a unique CDMA code that is modulated onto the navigation information signal. The receiver measures the time delay between transmitting and receiving the CDMA code to determine the distance to the satellite. By measuring the distance to multiple satellites, the receiver can determine its position in three-dimensional space and thus perform accurate ranging.

[2 marks]

d) If a GPS C/A code receiver is turned on with no knowledge of its location or any other information provided to it, how long does it typically take to get a navigation fix and why?

Answer:

When a GPS C/A code receiver is turned on without prior knowledge of its position or any other information, it typically takes 45-120 seconds to obtain a navigation position, which is known as a cold start. This is because, during a cold start, the GPS receiver needs to perform several tasks to acquire and track the GPS signal and determine its position. These tasks include:

Signal acquisition: The GPS receiver needs to detect the signal, synchronise with the GPS satellites, and identify the code phase and frequency of the signal. This process can take a few seconds or longer, depending on various factors such as the number of visible satellites, the strength of the GPS signal and the processing power of the receiver.

Ephemeris and Almanac data: A GPS receiver needs to receive precise position and time information from at least four GPS satellites to calculate its position. If the receiver does not know this data in advance, it must wait for the GPS signal to transmit this information, which can take several minutes.

Position calculation: Once the receiver has decoded all the satellite signals and acquired ephemeris data, it can calculate its own position using the triangulation method. This step can take from a few seconds to several minutes, depending on the performance of the receiver and the number of satellites available.

Clock synchronisation: Finally, the receiver needs to synchronise its local clock to the atomic clock of the GPS system. This step can be achieved by using the satellite signal transmission time calculated from a known position. By comparing the difference between the local clock and the GPS system clock, the receiver can calibrate its own clock and improve its positioning accuracy.

[4 marks]

2. a) In no more than 200 words describe the fundamental concept of how a GNSS system works and any technology which enables it?

Answer:

GNSS system works with three parts:

Space segment: comprises a constellation of satellites orbiting the Earth that transmit signals containing information about their precise position and current time.

Control segment: A network of ground control stations tracks the satellites and monitors their signals and uses this information to accurately determine the position of each satellite, ensuring that they transmit the correct time and position data. Corrections and updates are then uploaded to the satellites and transmitted to the user receivers.

User segment: This consists of the equipment that receives the signals transmitted by the satellites. The receiver uses the signals from multiple satellites to calculate its precise position on Earth. By analysing the timing and phase of the received signals, the receiver can determine the distance between itself and each satellite. By using trilateration, the receiver can then calculate its position on the Earth's surface.

GNSS technology includes atomic clocks that provide accurate time and frequency references for the satellite signals, digital signal processing that allows the receiver to process and analyse the complex signals received from the satellites, and satellite constellation design that ensures good coverage and accuracy for ground users.

[6 marks]

b) What is the length (period) of a chip for the GPS C/A code signal? How much is that in metres?

Answer:

The GPS C/A code signal has a frequency of approximately 1.023 MHz and the speed of light is 3×10^8, so its length is:

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8}{1.023 \times 10^6} = 293.26 \text{ m}$$

[4 marks]

3. **a)** What is the main lobe(s) bandwidth for a GNSS signal modulated with BPSK(**K**)? and BOC(1,1)?

Answer:

For BPSK (3), there is only one main lobe and bandwidth is twice as large as its code chipping rate:

$$Bandwidth = 2 \times code\_rate = 2 \times 3 \times f_o = 2 \times 3 \times 1.023\ MHz = 6.14\ MHz$$

For BOC (1,1), there are two main lobes:

$$Bandwidth = 2 \times 2f_o = 2 \times 2 \times 1.023\ MHz = 4.09\ MHz$$

[4 marks]

b) A GPS satellite is moving with a line of sight relative velocity of $(\boldsymbol{K} \times 400)$ m/s to a receiver. What is the Doppler shift to the centre frequency caused by this movement on the L1 and L2 signals from the satellite at the receiver?

Answer:

The velocity of the GPS satellite is (3×400)=1200 m/s.

Equation 13 is the formula to calculate the Doppler shifted frequency:

$$f' = f_o \frac{1}{1+\frac{v}{c}} \qquad \textbf{Eqn.13}$$

Thus, the Doppler shift to the centre frequency can be calculated as:

$$\Delta f = f' - f_o = f_o \frac{1}{1+\frac{v}{c}} - f_o \qquad \textbf{Eqn.13}$$

The frequency of the L1 signal is 1.575 GHz and the frequency of the L2 signal is 1.227 GHz. The Doppler shift to the centre frequency caused by this movement on the L1 "Δf_1" and L2 "Δf_2" signals are:

$$\mathit{\Delta} f_1 = 1.575 \times 10^9 \frac{1}{1 + \frac{1200}{3 \times 10^8}} - 1.575 \times 10^9 = -6299.97\ Hz$$

$$\mathit{\Delta} f_2 = 1.227 \times 10^9 \frac{1}{1 + \frac{1200}{3 \times 10^8}} - 1.227 \times 10^9 = -4907.98\ Hz$$

[8 marks]

c) A 10 MHz TXCO is driving a receiver's front end and has a frequency deviation of 4 ppm. It drives a direct downconversion RF front-end mixing the L2 frequency. What is the frequency offset at baseband due to the TXCO?

Answer:

The frequency of L2 is 1.277.6 MHz, the frequency offset at baseband due to the TXCO is:

$$f_{offset} = 4 \times 10^{-6} \times 1.277.6 \times 10^6 = 4910.40 \text{ Hz}$$

[4 marks]

4. What are the significant error sources of a GNSS and how they might be mitigated? Use 200 words or less, a bullet point list with descriptions is acceptable/preferred

Answer:

- **Knowledge of satellite positions:** Positions are constantly changing, and prediction errors can lead to inaccurate calculations, which can be mitigated by accurate orbital modelling.
- **Propagation delays in the ionosphere:** The ionosphere affects the speed of GNSS signals, causing ranging errors that can be mitigated with dual frequency receivers and single frequency or differential positioning models.
- **Tropospheric delay:** It affects GNSS velocity, causing ranging errors and impacting accuracy. Errors are reduced by model or differential positioning.
- **Tracking errors (from noise and interference).** These affect GNSS signals, causing errors in tracking and position calculations. This error can be

reduced by using a strong signal or a long averaging time to reduce the effect of noise.

- **Tracking errors (platform movement):** This can lead to dynamic tracking errors which can be mitigated by increasing loop bandwidth or integrating GNSS with inertial sensors for better positioning accuracy.
- **Multi-path:** Signal reflection causes position calculation errors due to interference. High bandwidth signals and narrow correlator receivers mitigate this error by distinguishing direct and reflected signals.
- **Blocking and attenuation:** Attenuation increases tracking errors; blocking can cause signal fluctuations and loss. This can be mitigated using multi-constellation receivers, enhancement systems providing additional signal/correction or differential positioning.

[10 marks]

End