A SunCam online continuing education course

Spacecraft Subsystems Part 5 – Fundamentals of Telemetry & Command

https://www.artstation.com/davidb

by

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Contents

1. Introduction **4**
Orbit Types 5
Voyager 1 6
2. Telemetry & Command **11**
RF Link Budget 11
Telemetry Transmission Process 15
Command Reception Process 16

Figures

Figure 1.1: Apollo 13's Mission Control 4
Figure 1.2: Common Earth Orbit Types 5
Figure 1.3: Voyager 1 Artist Rendering by David Benoist 6
Figure 1.4: Voyager 1 T&C Antenna 8
Figure 1.5: DSS-14 Ground T&C Antenna 8
Figure 1.6: Uplink Beam vs Downlink Beam.. 9
Figure 1.7: Voyager 1 RF Beam 10
Figure 2.1: Earth's Ionosphere 12
Figure 2.2: Rain Attenuation.. 13
Figure 2.3: Atmosphere Layers vs Ionosphere 14
Figure 2.4: Telemetry Flow Diagram 15
Figure 2.5: Command Flow Diagram 16

1. Introduction

Spacecraft are man-made machines that operate in space. An earth orbiting spacecraft is normally referred to as a satellite, although it is manmade (aka "artificial") as opposed to a natural satellite like our moon. A spacecraft is typically subdivided into two major parts, the payload and the bus. Where the mission can be defined as the purpose of the spacecraft and is usually identified as the payload part of the spacecraft (e.g. scientific instruments, communications). The telemetry & command subsystem and other subsystems (e.g. attitude control, electrical power, thermal control, propulsion) are part of the bus. With the primary goal of achieving a successful mission, most bus design constraints focus on maximizing the effectiveness of its payload [ref. 1]. Spacecraft can operate in deep space (interplanetary or interstellar) or as a satellite orbiting the earth. Interstellar space is about 12 billion miles from the sun. This is the distance where our sun no longer effects the space environment.

Telemetry & Command (T&C) in the context of this course refers to the ability of a spacecraft to communicate with its mission control ground station, transmitting measurement information (i.e. telemetry) and receiving commands. One well known example was Apollo 13's mission control in Houston, Texas, captured in the following image on April 13, 1970. The telemetry data displayed on screens (and voice communications) allowed ground controllers to instruct (i.e. command) the astronauts on what procedures to perform in able to return to safety home.

Figure 1.1: Apollo 13's Mission Control
[Reprint from source: NASA @ nasa.gov]

<u>Note: All figures in this course have no scale, unless noted otherwise.</u>

Orbit Types

A satellite's operating environment largely depends on its orbit type, which is primarily driven by its intended mission. The three common earth orbiting satellite types are geosynchronous orbit (GEO), highly elliptical orbit (HEO), and low earth orbit (LEO) as seen in the following figure [ref. 1].

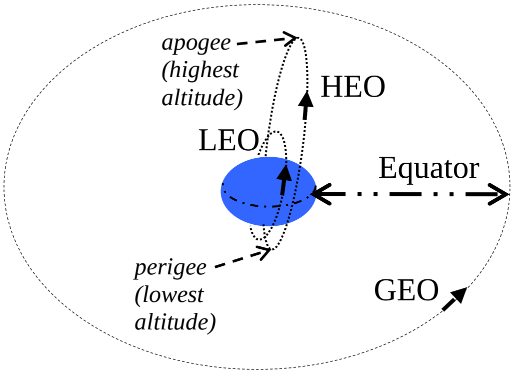

Figure 1.2: Common Earth Orbit Types
[Reprint from source: ref. 1]

LEO satellites have an altitude of less than one thousand miles. Satellites in HEO can have a wide ranges of altitudes for perigee (lowest altitude) to apogee (highest altitude) [ref. 2].

GEO satellites, orbiting about the equator at some small angle (inclination angle), have an altitude of ≈ 23,000 miles above earth. At this altitude, satellites have the same period of rotation as the earth, appearing fixed relative to earth. Because of this, these satellites are most commonly used for communications purposes (e.g. television) since there is no need for the receive dish on earth to track the satellite [ref. 1].

RF energy travels at the speed of light, $3x10^8$ m/s (186,000 mi/sec). Therefore, for GEO satellites, it takes 1/8th of a second for both uplink and downlink signals to reach the receive antenna. This delay is known as propagation delay. When a satellite's payload is used for communications (e.g. to relay a television signal), this delay would combine to be 1/4 of a second. You may have seen this when watching a live television broadcast, especially if multiple (relay) satellites are between the transmission-to-reception (ground-to-ground) path.

Voyager 1

One relic of the past and still going is the Voyager 1 spacecraft, now so far away, that the RF T&C signal propagation delays are extreme. As of January 13, 2018 it took 19:37:24 (hh:mm:ss) for an RF signal (one-way) to get to or from the spacecraft [ref. 6].

One unique example, Voyager 1, shown in the following artist's rendering by my son David Benoist – https://www.artstation.com/davidb, which represents an early view of Voyager 1's white high gain antenna (HGA) pointing to earth. Also notice the golden record on top of the spacecraft in this view which contains the history of our culture in case Voyager 1 is seen by "others".

https://www.artstation.com/davidb

Figure 1.3: Voyager 1 Artist Rendering by David Benoist

As mentioned, the previous image depicts an early impression of Voyager 1 when it was relatively close to earth. It is now a mind boggling 13.1+ billion miles away traveling at about 35,000 mph. The spacecraft used the intense gravitational forces of jupiter to sling-shot around it, accelerating to a speed of over 35,000 mph. Voyager 1, reached interstellar space in August 2012.

Recently, on Tuesday, Nov. 28, 2017, the T&C system was used to test thrusters successfully. These thruster had been dormant for 37 years. These monopropellant hydrazine thrusters will be used for attitude control to extend Voyager 1's mission life by a few years, enabling its white parabolic dish antenna to continue pointing toward earth. The downlink signal took 19 hours and 35 minutes to reach the receive antenna in Goldstone, California.

Because of spacecraft mass constraints, for deep space missions as in Voyager 1, the ground T&C antenna needs to be much larger than the spacecraft's T&C antenna. For parabolic dish type antennae, power is directly proportional to the diameter of the dish. Because of this, Voyager 1's 3.7 meter (12 foot) HGA produces much less power than its huge ground system antenna located at Deep Space Station 14 (DSS-14). DSS-14's antenna (aka Mars Antenna) is 70 meters (230 foot) and is located in Goldstone, CA. This giant antenna is so sensitive it can receive a signal as weak as $1x10^{-18}$W, and therefore can easily pick up a mosquito buzzing above it generating about a picowatt of power ($1x10^{-12}$W). The power received currently by DSS-14 from Voyager 1 is about $1x10^{-16}$W. Both antennae are shown on the next page for size comparison. Voyager1's image is also inset with DSS-14 to provide scale.

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Figure 1.4: Voyager 1 T&C Antenna
[Reprint from source: NASA @ nasa.gov]

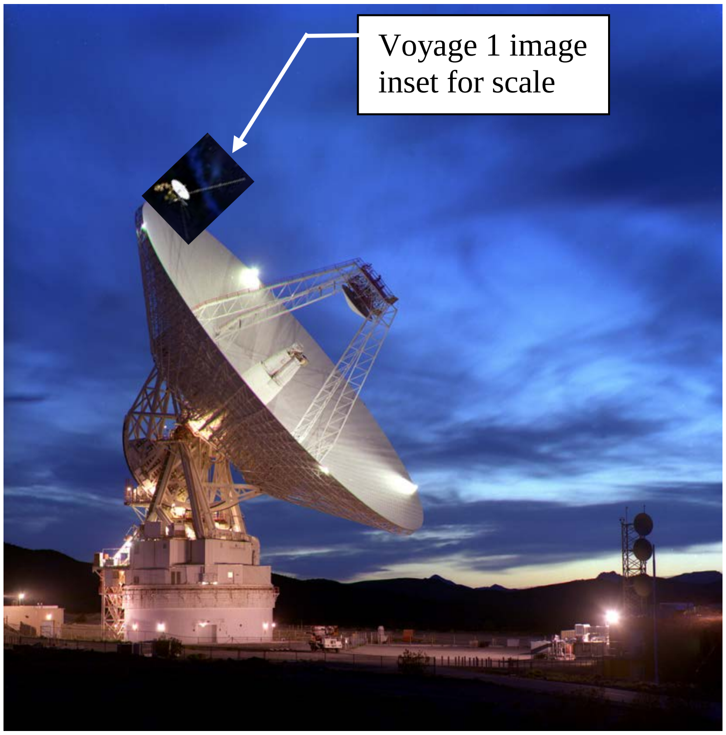

Figure 1.5: DSS-14 Ground T&C Antenna
[Reprint from source: NASA @ nasa.gov]

The following figure is an example of uplink and downlink beam coverage cones. Notice the much larger ground antenna of DSS-14 provides a narrow uplink beam. This is able to focus much of the power in order to provide a stronger signal at Voyager 1's receiver. In contrast, since Voyager 1 has a smaller dish antenna, the power from its small 22W transmitter is spread out over a larger area, therefore the downlink signal is weaker at DSS-14's receiver. Because of these two extremes, dish size and transmitter power of 20kW, DSS-14 can communication with deep space spacecraft such as Voyager 1.

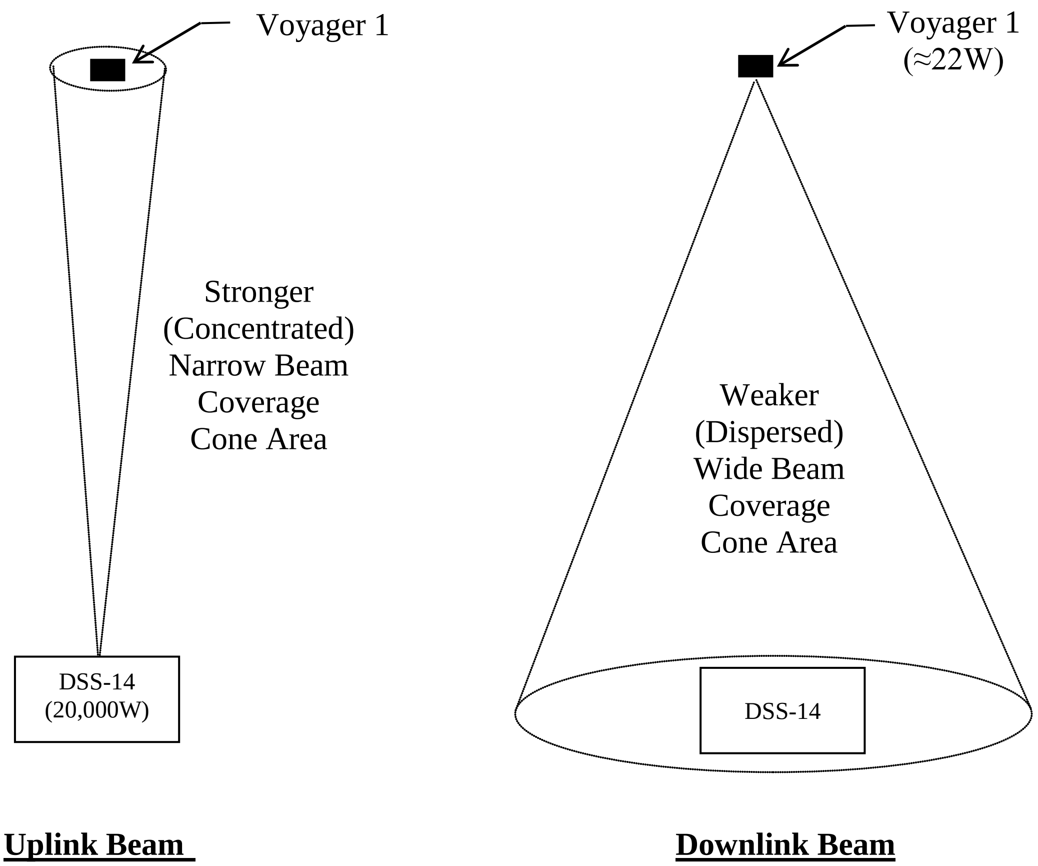

Figure 1.6: Uplink Beam vs Downlink Beam

There it is! Can you see it in the center of the following image? It's Voyager 1! The most distant manmade object – NASA's Voyager 1 spacecraft at 11.5 billion miles from earth, its RF downlink was captured by our earth-based National Radio Astronomy Observatory's 5,000-mile-wide Very Long Baseline Array (VLBA) while testing their sensitivity, Feb. 21, 2013.

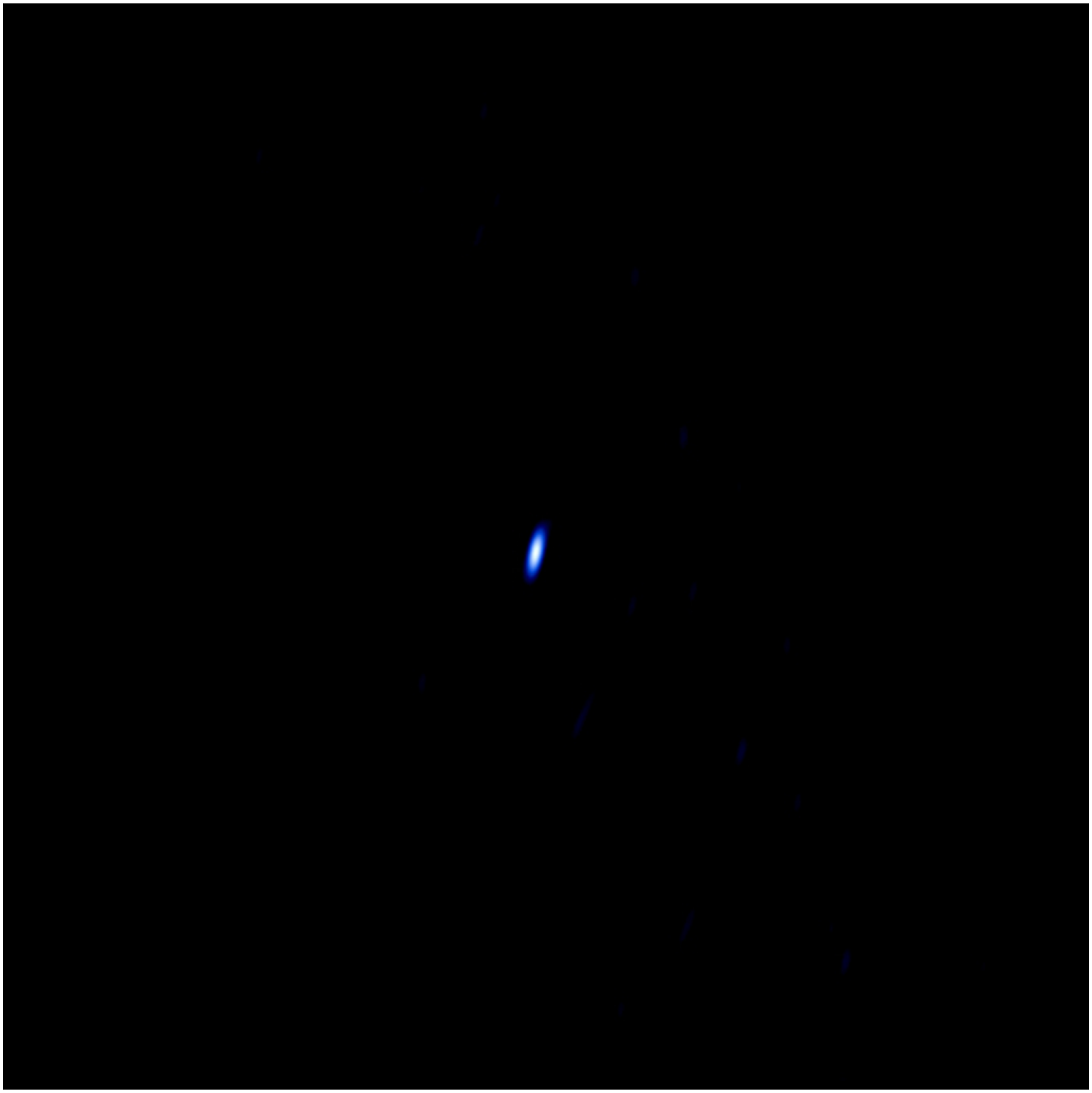

Figure 1.7: Voyager 1 RF Beam
[Reprint from source: NASA @ nasa.gov]

2. Telemetry & Command

Crucial to the Telemetry & Command subsystem is the RF downlink for telemetry transmissions and RF uplink for command receptions. A common frequency range used for the RF signal in spacecraft communications is the super high frequency (SHF) range of 3-30 GHz.

A key characteristic of the RF downlink and RF uplink is their RF link power, which must be strong enough for successful communications between the spacecraft and its mission ground station.

RF Link Budget

RF link budgets are used to ensure the required signal strength over uplinks and downlinks, where power is measured in decibels (dB) because the terms can be summed. This budget is similar in concept to a personal spending budget, where income is a positive, summed with a lot of negatives (e.g. auto loan, rent or mortgage, electric, phone, television, etc...) representing losses. Also like a personal budget, a spacecraft's RF link budget only has a few positives, but many negatives (losses). All losses act to attenuate (weaken) the RF receive signal.

For reliable spacecraft communications, a strong enough signal (+dBW) must be received by the uplink and by the downlink. This is achieved by determining a key parameter for uplink and downlink – called link margin. Link margin (dB) is the difference in ratios between the required signal-to-noise and the actual signal-to-noise.

Both uplink and downlink budgets can be expressed by the following equation:
$P_R = P_{eirp} + G_R - L_{FS} - L_{RF} - L_{AM} - L_{AA} - L_{ion} - L_R$
...where a difference in just +3dB is equivalent to double the power or -3dB to one-half the power. Each term is defined as follows (some brief, others in more detail):

P_R - received power (dBW) represents the signal strength at the receiver.

- Uplink - Spacecraft receiver
- Downlink - Ground receiver

P_{eirp} - effective isotropic radiated power (dBW) is the product of the transmitter power and antenna power gain.

- Uplink - Ground transmit
- Downlink - Spacecraft transmit

G_R - receiver gain (dB) represents the transmit gain of the receive antenna.

- Uplink - Spacecraft receive antenna
- Downlink - Ground receive antenna

L_{FS} - free-space spreading loss (dB)
Free space loss is a result of the spreading of the signal between a transmit antenna and a received antenna. This loss is a function of the distance and frequency - the higher one or both are, the greater the loss is. This loss value will be the most dominant of all other losses.

L_{RF} - receiver feeder loss (dB)
Receiver feeder losses are those attributed to the components between the receive antenna and the receiver: waveguides, filters, and couplers.

L_{AM} - antenna misalignment loss (dB)
For maximum gain, uplink and downlink satellite antennae must be precisely aligned. This loss accounts for a common, but small misalignment.

L_{AA} - atmospheric absorption loss (dB)
Losses attributed to absorption of RF energy by atmospheric gas molecules (e.g. water vapor and oxygen).

L_{ION} - ionospheric losses (dB)
All spacecraft RF signals are subject to the degrading effects caused by free electrons as they pass through the ionosphere (50-360 miles) due to scintillation and polarization rotation.

- scintillation: Time varying ionospheric irregularities can affect the following radio wave properties: amplitude, polarization, phase, and arrival angle. This results in attenuation of the signal by fading, which is a gradual decrease in signal strength.

The following figure depicts the non-uniform swelling in response to solar radiation in purple of the ionosphere, and therefore changes day and night.

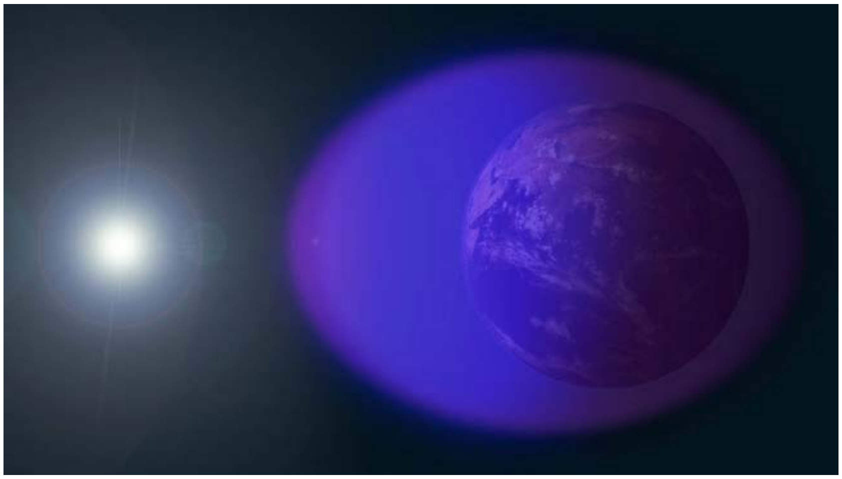

Figure 2.1: Earth's Ionosphere
[Reprint from source: NASA's Goddard Space Flight Center/Duberstein]

- polarization rotation: Refers to how linearly polarized RF waves interact with the ionosphere and earth's magnetic field, which causes an angular shift in direction of its electric field vector. Also known as Faraday rotation, the negative effects caused by this phenomenon are a function of frequency. Hence, this is not a concern greater than about 10GHz. Also, circular polarization of the RF signal uplink and/or downlink can be used to minimize this effect.

One example of an extreme ionic loss happens as a spacecraft reenters earth. For example, as experienced in the space shuttle or Apollo manned missions. The space vehicle as it reentered the earth's atmosphere was engulfed in a hot plasma sheath, causing an attenuation of up to 80dB, known as a communications "blackout", essentially acting as a barrier to RF signals.

L_R - rain loss (dB)

For those of you who have experienced satellite television outages during a rainstorm (as likely would happen in the following image of a distant rain), you have experienced the effects of rain loss. Raindrops effect the radio waves by absorbing and/or scattering them, thereby weakening the magnitude of their RF energy. Wavelength is inversely proportional to frequency, as frequency increases, the length of the waves decreases approaching the size of a raindrop (0.5-4mm), attenuation worsens. We can use the following equation to convert between frequency and wavelength: $f=c/\lambda$...where λ is wavelength in meters, f is frequency in hertz, and c is speed of light in meters per second

For example:
At SHF of 3GHz (min), wavelength = 0.1m (100mm)
At SHF of 30GHz (max), wavelength = 0.01m (10mm)

Figure 2.2: Rain Attenuation
[Reprint from source: wikimedia.org]

Rain prediction models such as Crane or ITU can be used to help calculate rain attenuation by providing intensity using rain rates (mm/hr) and average annual rainfall as percentage. These statistical characteristics, identified by geographic region, will help determine availability. Availability determines how often the rain rate will be exceeded. This percentage, usually very high, represents the average time per year that reliable communications can be expected. For example, if downlink availability is 98% over one region, then 2% of the time annually a communications outage can be expected due to rain.

Depending on mission, rain attenuation may or may not be necessary to include as a loss in link budget calculations. For example, if the beam coverage area is expected to cover a relatively dry area (e.g. Sahara desert), the rain attenuation term would not likely need to be included in the equation. However, if the beam coverage area is over an area with high average annual rain fall and rain rates (e.g. Amazon jungle), then rain attenuation would be a factor and included in the link budget equation as another loss term.

The following figure depicts the earth's atmospheric layers in relation to the ionosphere. As you can see, the ionosphere extends from about the mesosphere through to the outer layer exosphere. Also shown is the daytime electron density profile that varies with altitude (on right). Since these densities also varies over time, at night, the D region drops and F2 combines with F1 into just an F region. Most weather, like rain, occurs at the lowest layer – troposphere.

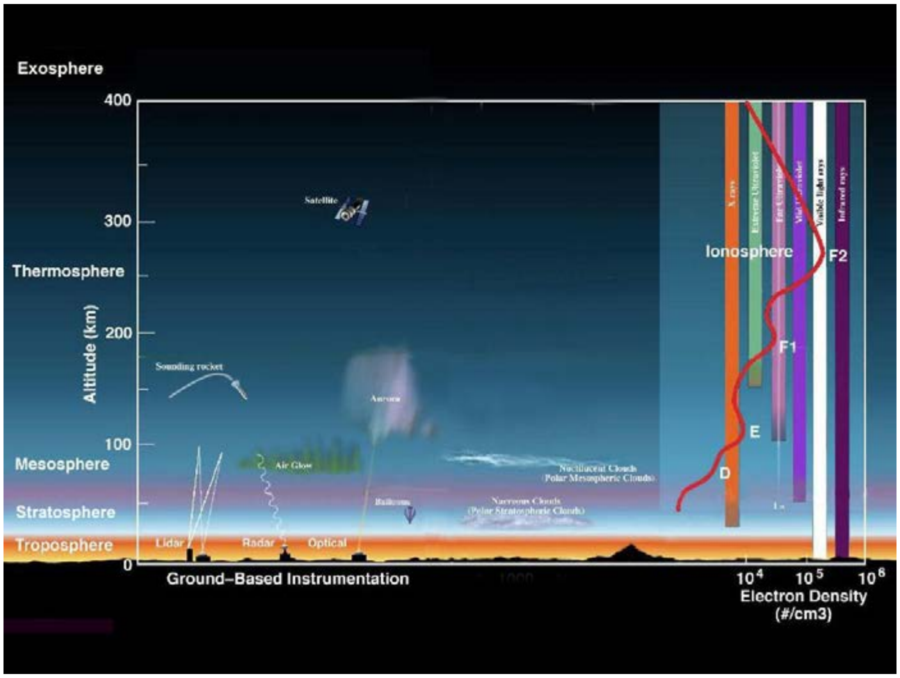

Figure 2.3: Atmosphere Layers vs Ionosphere
[Reprint from source: NASA @ nasa.gov]

Telemetry Transmission Process

Telemetry can be described by breaking down and defining this word by its parts as follows:

- *"tele-"* = at or over a long distance
- *"-metry"* = process of measuring

Since most spacecraft are unmanned, telemetry is crucial to any mission. Telemetry status parameters must be monitored as much as possible to understanding its health. Parameters from all spacecraft subsystems are contained in telemetry data for ground analysis by computers, engineers, and scientists. The following are some examples of the types of telemetry data by subsystem:

- Attitude Control: pitch, roll, yaw
- Electrical Power: battery and solar array voltages, battery depth of discharge
- Thermal Control: temperatures, heater usage
- Propulsion: fuel level, pressures, burn duration
- Payload: scientific measurements

The main functional stages/components of the telemetry transmission process are:

- Acquisition: sensors, analog-to-digital converters
- Processing: computer
- RF Downlink: transmitter/antenna

The following sequence of events are needed for successful spacecraft telemetry transmission:

1. Telemetry inputs are acquired using various components (e.g. sensors, A/D converters).
2. Computer processes telemetry inputs by compressing, formatting, then storing it as binary data for later transmission, or sends it immediately to the RF downlink.
3. RF downlink transmits telemetry data to ground system with enough power ($\underline{P_{eirp}}$) to ensure link margin requirements are met as previously described.

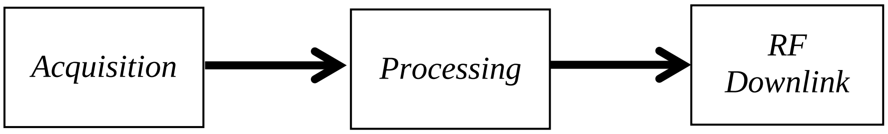

Figure 2.4: Telemetry Flow Diagram

Command Reception Process

The purpose of commands is to allow control of the spacecraft bus components or payload when necessary. Command data is sent by the mission's ground system to the spacecraft for immediate execution or stored for later use. The following are some examples of the types of command data by subsystem:

- Attitude Control: hardware switching between primary/redundant (A/B)
- Electrical Power: solar array pointing
- Thermal Control: actuation of louvers
- Propulsion: burn/thrust execution
- Payload: scientific experimental

The main functional stages/components of the command reception process are:

- RF uplink: receiver/antenna
- Processing: computer
- Signal Interface

An essential component of the RF uplink, the receiver, is normally designed to be continuously powered on. An early flight mission was lost because the spacecraft's receiver was mistakenly turned off. Well, if you turn the receiver off, how can it receive a command to turn it back on?

The following sequence of events are needed for successful spacecraft command reception:

1. RF uplink receives command data from ground system with enough power (P_R) to ensure link margin requirements are met as previously described.
2. Computer validates binary command data then either stores it for later execution or sends it directly to the signal interface.
3. Signal interface sends an analog or digital command signal to an end component (e.g. switch/valve) to perform an action (e.g. open/close). It can also send the command information to another subsystem computer for storage, further processing, or execution.

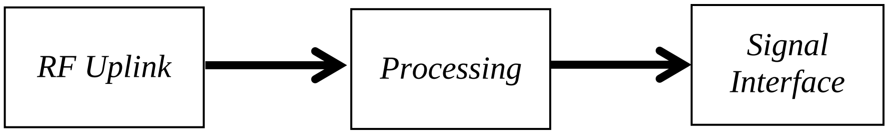

Figure 2.5: Command Flow Diagram

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Note: If there was no date on a sourced website article, the year the article was accessed was used.