Professional Development Short Course On:

Ground System Design & Operation

Instructor:

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Preface

In preparing this presentation I have discovered that it is more difficult to select meaningful highlights than it is to simply teach the course. I have attempted to distill over 350 slides into a cohesive overview of this course.

The challenge has been to provide a smattering of slides that capture the breadth of the course material without being either overwhelming in quantity or underwhelming in quality.

Hopefully I have been successful in capturing the essence of the class.

Ground System Design and Operations
In discussing “Spacecraft Ground Systems” a frequent issue results from the different meaning associated with the term depending on ones vantage point. In this class I strive to provide a uniform level of understanding that encompasses the entire spacecraft ground system, beginning with the reception of radio signals by the antenna and continuing right through to the display of telemetry. In this way the student gains a through understanding of how compromises made in one area affect other areas of the Ground System. The result is a better understanding of overall system capabilities and the ability to better optimize performance.

Ground System Design and Operations
1. **The Link Budget:** Basic communications principles and theory; losses, propagation, and system performance

2. **Ground Station Architecture and System Design:** Ground station topology, system elements and technology

3. **Ground Station Elements:** Major subsystems, including their roles, parameters, limitations, and tradeoffs

4. **Figure of Merit (G/T):** The key parameter used to characterize ground station performance, bringing all ground station elements together as a system

5. **Modulation Basics:** Signal sets, analog and digital modulation schemes, and performance parameters
6. **Ranging and Tracking**: an introduction to the concepts of orbital elements sets and a discussion of the acquisition of the data needed for orbit determination and propagation

7. **Ground Station Networks and Standards**: Existing and planned ground station networks and standards including applicability, advantages, and disadvantages of each

8. **CCSDS**: A primer on the CCSDS Recommendations for telecommand and telemetry formats for space missions including an overview of CFDP

9. **Beyond the Ground Station**: An overview of ground system design beyond the boundary of the physical layer
10. **Ground Station Operations:** An overview of day-to-day operations in a typical ground station including general management, daily planning, pass execution, data processing and analysis, and maintenance.

11. **Trends in Ground Station Design:** The positive impact of the “Faster, Better Cheaper” approach on Ground Station design and operation, including the value added by emergent COTS hardware and software systems, new trends in autonomy, and “lights out” operations.
A link budget is developed using the generalized Link Equation and the selected or anticipated link parameters. This link budget is used to predict either the anticipated link performance at a specified margin or the anticipated margin at a specified performance level (e.g., bit rate). Link budgets are generally shown as columnar sums which lend themselves to computer spreadsheets. A sample Link Budget is shown on the following page; this Link Budget spreadsheet is available upon request.
Sample Link Budget Spreadsheet

- This sample spreadsheet was developed using Microsoft Excel
- Parameters shown in shaded boxes are entered by the user; those in the white boxes are calculated by Excel
- This spreadsheet gives performance in a variety of parameters including C/N, C/No, and Eb/No, each of which is applicable to a different type of link; these will be covered in detail
Ground Station Block Diagram

Ground System Design and Operations
G/T Model

• To understand G/T, it is useful to have a system model where each contribution to G/T can be mapped out and intuitively understood, as shown in the figure below:

![G/T Model Diagram](image)

Ground System Design and Operations
Noise due to Subsequent Gain Stages

- Since the noise contribution of all gain stages must be reflected back to the reference point, the noise contribution of each stage must be divided by the gain of earlier stages to represent an equivalent noise source at the reference point.
- For three gain stages following the LNA of $G_1$, $T_1$, $G_2$, $T_2$, $G_3$, and $T_3$, the equivalent total noise temperature is:

$$T_{\text{equivalent}} = T_{LNA} + \frac{T_1}{G_{LNA}} + \frac{T_2}{G_{LNA}G_1} + \frac{T_3}{G_{LNA}G_1G_2}$$

Ground System Design and Operations
## A Sample Spreadsheet Calculation

<table>
<thead>
<tr>
<th>Component</th>
<th>Gain (dB)</th>
<th>Temp (K)</th>
<th>Temp (dBK)</th>
<th>Loss (dB)</th>
<th>Tref (dBK)</th>
<th>Gref (dB)</th>
<th>Tref (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna</td>
<td>23.50</td>
<td>90.00</td>
<td>19.54</td>
<td>-1.45</td>
<td>18.09</td>
<td>23.50</td>
<td>64.45</td>
</tr>
<tr>
<td>Coaxial Cable</td>
<td>-0.50</td>
<td>31.54</td>
<td>14.99</td>
<td>-0.95</td>
<td>14.04</td>
<td>-0.50</td>
<td>25.34</td>
</tr>
<tr>
<td>Diplexer</td>
<td>-0.85</td>
<td>51.55</td>
<td>17.12</td>
<td>-0.10</td>
<td>17.02</td>
<td>-0.85</td>
<td>50.38</td>
</tr>
<tr>
<td>HPA Leakage</td>
<td>72.46</td>
<td>18.60</td>
<td>-0.10</td>
<td>18.50</td>
<td>70.81</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coaxial Cable</td>
<td>-0.10</td>
<td>6.60</td>
<td>8.20</td>
<td>0.00</td>
<td>8.20</td>
<td>-0.10</td>
<td>6.60</td>
</tr>
</tbody>
</table>

### Reference Point

<table>
<thead>
<tr>
<th>Component</th>
<th>Gain (dB)</th>
<th>Temp (K)</th>
<th>Temp (dBK)</th>
<th>Loss (dB)</th>
<th>Tref (dBK)</th>
<th>Gref (dB)</th>
<th>Tref (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNA</td>
<td>30.00</td>
<td>62.69</td>
<td>17.97</td>
<td>0.00</td>
<td>17.97</td>
<td></td>
<td>62.69</td>
</tr>
<tr>
<td>Downconverter</td>
<td>30.00</td>
<td>2610.00</td>
<td>34.17</td>
<td>-30.00</td>
<td>4.17</td>
<td></td>
<td>2.61</td>
</tr>
</tbody>
</table>

**LNA Noise Figure (dB)** 0.85  
**Downconverter Noise Figure (dB)** 10.00

### Totals

<table>
<thead>
<tr>
<th>G (dB)</th>
<th>T (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>22.05</td>
<td>282.89</td>
</tr>
</tbody>
</table>

**HPA In-band Noise (dBW/Hz)** -90.00  
**HPA Temperature (dBK)** 138.60  
**Diplexer Isolation, TX-RX (dB)** -120.00  
**HPA Leakage (dBK)** 18.60  
**HPA Leakage (K)** 72.46  

**Ambient Temperature (K)** 290.00  
**Boltzmann's Constant (dBW/Hz-K)** -228.60

**G/T (dB/K)** -2.47

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**Reference G/T model depicted on page 4-5**

Ground System Design and Operations
This section will proceed through a typical Ground Station subsystem by subsystem, as outlined previously in Section 2, breaking each subsystem into components and describing each of those parts in a much greater level of detail.
Antenna Systems

- The antenna system is synonymous with the Ground Station in the eyes of most neophytes; who can think of a ground station without picturing a large antenna, generally a parabolic reflector or “antenna dish”?
- Accordingly, this first section will be devoted to antenna systems and antenna designs and characteristics.
- Before beginning any detailed discussion of antenna subsystems, it is important to define some key parameters.
Antenna Temperature

- An antenna exhibits a certain antenna temperature ($T_A$); this is the temperature of a blackbody which would produce an equivalent noise power as the antenna.
- $T_A$ is a function of antenna pattern, the surrounding environment, and the direction of antenna pointing; for a highly directional antenna pointed at “cold” space, the noise power coupling into the back lobe of the antenna from the “hot” earth has little effect on the overall low $T_A$.

\[ T_A = \iiint G(\theta, \phi)T(\theta, \phi)d\theta d\phi \]

- $T_A$ is an important factor in overall ground station G/T.
Dish Gain Derivation

\[ G = A_e \frac{4\pi}{\lambda^2} \quad \Rightarrow \quad G = \eta A \frac{4\pi}{\lambda^2} \quad \Rightarrow \quad G = \eta \pi r^2 \frac{4\pi}{\lambda^2} \]

\[ \Rightarrow \quad G = \eta \pi \left( \frac{D}{2} \right)^2 \frac{4\pi}{\lambda^2} \quad \Rightarrow \quad G = \eta \frac{4D^2\pi^2}{4\lambda^2} \]

\[ \Rightarrow \quad G = \eta \frac{D^2\pi^2}{\lambda^2} \quad \Rightarrow \quad G = \eta \left( \frac{D\pi}{\lambda} \right)^2 \]
Antenna Pointing and Tracking Systems

• A large or high gain antenna must be carefully pointed to receive energy from a desired spacecraft; this can be compared to observing a target through a soda straw or high-magnification telescope. If the target is not in the field of view, the signal will not be received.

• The purpose of the antenna pointing and tracking system is to acquire the satellite, or get it into the field of view of the antenna, and track the satellite, i.e., keep the spacecraft in the field of view or main beam of the antenna so that data can be transmitted and received both ways.
Antenna Pointing and Tracking Systems

- There are three common methods for pointing and tracking an antenna system for a ground station:
  - Open Loop
  - Step Track
  - Monopulse

- Each of these pointing and tracking systems will be described in greater detail in the charts which follow; while these systems are not all-encompassing, they account for most commercially developed and built ground stations
Low Noise Amplifiers

- In the next section, we will discuss the calculation of the ground station Figure of Merit, or G/T, which is a key parameter in establishing a ground station’s performance.
- In G/T, it will become clear that the noise performance of the first active gain stage in the ground station is absolutely critical in establishing the system’s performance level.
- This first gain stage is called the Low-Noise Amplifier, or LNA; improvements in LNA performance have driven improvements in ground station performance and utility more than any other single area of technology development.
High Power Amplifiers

• The last active device in the transmit chain before the antenna feed assembly is the Power Amplifier (PA), also frequently referred to as the High Power Amplifier (HPA)

• There are three major types of HPA commonly in use in Ground Station transmission systems today:
  – Traveling Wave Tube Amplifiers (TWTAs)
  – Klystrons
  – Solid State Power Amplifiers (SSPAs)

• Each will be briefly described in the charts that follow
Frequency Conversion

- The modulation and demodulation of data carrying signals tends to be performed at relatively low frequencies in the 10-400 MHz range for reasons of convenience; design topologies and components that operate properly in this frequency band are well understood and easily fabricated.
- Transmission of carriers tends to be in the 1-40 GHz range for space communications due to the availability of bandwidth and the physics of atmospheric propagation.
- As long as this continues to be the common practice, frequency conversion systems will continue to be needed.
Understanding Modulation Basics

• An unmodulated signal, or carrier conveys no information
• To be useful, it is necessary to modulate the carrier, i.e., to vary some element of the carrier in a way that information is conveyed and can be recovered by the demodulator
• An RF signal, or carrier, has several characteristics that can be modulated in a manner that can be detected so the original modulating signal can be reproduced, including:
  – Amplitude
  – Frequency
  – Phase
Phase Modulation

- In Phase Modulation, or PM, the phase of the carrier is modulated as a function of the input signal.

- The PM signal can be described mathematically:
  \[ F(t) = A \sin(\omega t + \phi(t)) \]
  where \( \phi(t) \) is the modulating signal.
Digital Communications Overview

Original Signal ➔ Bandlimiting ➔ Sampling ➔ Quantizing ➔ Encoding ➔ Transmission

8, 34, 51, 50, 36, 11, -41, -50, -48, -38, ...

001101101
100010101001100010
10100010...

Reproduced Signal ➔ Filtering ➔ Digital-to-Analog Conversion ➔ Decoding ➔ Reception

8, 34, 51, 50, 36, 11, -41, -50, -48, -38, ...

001101101
100010101001100010
10100010...

Ground System Design and Operations
Signal Constellation Examples

- It is useful at this time to represent signal constellations in phase and amplitude space; each symbol, which has its own phase and amplitude, corresponds to a number of bits.
- Errors are generated when the vector addition of noise causes the resultant signal to cross a decision boundary into the signal space of another symbol, resulting in errors.
CCSDS Telecommand System

**Layers**

Telecommand, Part 3
Data Management Service

Application Process Layer
  - Command Directive
  - System Management Layer
  - TC Application Data
  - Packetization Layer

Packet

Segmentation Layer
  - Segment
  - Transfer Layer
  - Transfer Frame

Coding Layer
  - CLTU
  - Physical Layer
  - Physical Waveform

Service Provided by Layer

Allows human users to supervise remote processes by interfacing with space telecommand systems.

Converts user command directives into transportable application data units and supervises their delivery and execution.

Transports application data units in an error-free manner to the receiving end of the System Management layer on the spacecraft.

Breaks long higher-layer TC Data Units into shorter communications-oriented pieces and multiplexes different data units together (optional services).

Reliable transfers higher layer TC Data Units to the spacecraft through the space data channel under error-controlled conditions.

Protects higher layer TC Data Units against errors induced during transmission through the physical path to the spacecraft.

Provides the physical connection, via radio frequency signals, between a transmitting station and the receiving spacecraft.
Telecommand Data Structures

Ground System Design and Operations
Telemetry Transfer Frame Format

<table>
<thead>
<tr>
<th>Sync Marker</th>
<th>Frame Identification</th>
<th>Master Channel Frame Count</th>
<th>Virtual Channel Frame Count</th>
<th>Frame Data Field Status</th>
<th>Transfer Frame Data Field</th>
</tr>
</thead>
<tbody>
<tr>
<td>Version #</td>
<td>S/C ID</td>
<td>Vir. Chan ID</td>
<td>OCF Flag</td>
<td>Sec. Header Flag</td>
<td>Spacecraft Application Data</td>
</tr>
<tr>
<td>32</td>
<td>2</td>
<td>10</td>
<td>3</td>
<td>1</td>
<td>(Variable)</td>
</tr>
</tbody>
</table>

Secondary Header ID
- Sec. Header Version # (2)
- Sec. Header Length (6)
- Secondary Header Data (Up to 504)

Optional Transfer Frame Secondary Header
- Operational Control Field (32)
- Frame Error Control Word (16)

Optional Transfer Frame Trailer

Ground System Design and Operations
CFDP At A Glance

Ground System Design and Operations
Convolutional Encoder

The Encoder pictured below with constraint length $N = 3$ and $\nu = 2$ modulo 2 adders will produce the output code sequence shown in response to the input sequence below.

+ = Modulo 2 addition = XOR

$$s_1 = d_1 \oplus d_2 \oplus d_3$$

$$s_2 = d_1 \oplus d_3$$

Input Sequence
11010

Output Sequence
0011010100101100

<table>
<thead>
<tr>
<th>$d_1$</th>
<th>$d_2$</th>
<th>$d_3$</th>
<th>$s_1$</th>
<th>$s_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
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<tr>
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<td>0</td>
</tr>
</tbody>
</table>
Ground System Design and Operations

Ground System Block Diagram

- Command Generator
- Telemetry Interpreter
- Command Dictionary
- Telemetry Packetizer
- Telemetry Encoder
- Command Exciter
- Diplexer
- Receiver
- Bit Sync
- Telemetry Decoder
- Channel Separator
- Telemetry Deframer
- Telemetry Interpreter
- Telemetry Dictionary
- HPA
- LNA

Front End:
- CLTUs
- TC Frames
- TC Packets
- CMD Language

MOC HW/SW:
- TLM Frames
- TLM VCs
- TLM Packets

Ground Station:
- TLM Clk & Data

USER
TIMED End to End Data System*

* End to End Data System Figure courtesy of P. J. Grunberger, The Johns Hopkins University Applied Physics Laboratory

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