Seminar 11
Commercial Space Flight
Telemetry, Communications, & Tracking
FRS 104, Princeton University
Robert Stengel

New Space Race
Aerospace Companies
Roles of NASA and DoD

Antennas and Signal Propagation
Signal Detection and Noise
Deep Space Network

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http://www.princeton.edu/~stengel/FRS.html

2004 Estimates
Strategy Based on Long-Term Affordability

NOTE: Exploration missions – Robotic and eventual human missions to Moon, Mars, and beyond
Human/Robotic Technology – Technologies to enable development of exploration space systems
Crew Exploration Vehicle – Transportation vehicle for human explorers
ISS Transport – US and foreign launch systems to support Space Station needs especially after Shuttle retirement
2004 Estimates
Exploration Roadmap

- CEV Contract Award
- Orion/ARES Operational
- Lunar Outpost Buildup
- Lunar Robotic Missions
- Science Robotic Missions
- Commercial Crew/Cargo for ISS
- Space Shuttle Operations
- Orion CEV Development
- ARES I Launch Vehicle Development
- Early Design Activity
- Lunar Lander Development
- Lunar Heavy Launch Development
- Earth Departure Stage Development
- Surface Systems Development

Note: Specific dates and milestones not yet established. CEV/OLV availability planned for at least by 2010 as possible, but no TDR in 2014. Refer to the most recent estimate at 2014. TDR November 2020.

LUNAR FLIGHT PLAN

- NASA Proposal to Return Humans to the Moon
  - Constellation Program, 2004
  - Underbudgeted, as noted by Augustine ('59, '61) Commission
  - Cancelled by Congress in 2011
... But NASA’s Budget was and is Too Small to Accomplish the Program

Chinese, Japanese, and Indian Lunar Exploration Programs

Chang’e-3 Lander (2013)  
Jade Rabbit “Yutu” (2013)  
SELENE-2 (2017)  
Chandrayaan-2 (2017)  

WHAT’S LEFT OF A SOARING VISION ...

2008: Lunar robotic orbiter
2009: Annual lunar robotic landers begin
2011: Mars demo lander mission
2012: Mars robotic sample return
2014: Test flight of shuttle replacement
2015: Nuclear power/propulsion demo
2018: Astronauts return to the moon
The New Space Race

Los Angeles Times

The new space race: It's not just the U.S. and Russia anymore

There are now many space programs, both national and private. And that's good for science.

January 28, 2014

US and Foreign Heavy-Lift Launch Vehicles

Why is China targeting the moon -- and should NASA as well?

By Jeremy Kaplan / Published December 06, 2013 / FoxNews.com

Jan. 28, 2014: Russian Space Agency Plans World’s Biggest Rocket
US and Foreign Manned Spacecraft

Commercial Enterprise May Hold the Key

But ... Is NASA spreading itself too thin by supporting commercial enterprise AND developing the ORION-SLS vehicles?
$20M prize for first craft to
  - Land on the Moon, move 500 m, and send video back to Earth by End of 2015
  - 18 contenders

“Milestone” prizes ($6M total) for achieving intermediate objectives by Sept 2014
  - US (2), Indian, German, and Japanese finalists

Actual mission cost estimates: $10-100M

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David Thompson, Co-founder, Orbital Sciences, 30th Anniversary

https://www.youtube.com/watch?v=5Dlkelj7mBg

Elon Musk, CEO, SpaceX, on 60 Minutes


Richard Branson, CEO, Virgin Galactic, and Burt Rutan, CEO, Scaled Composites, promotional trailer

https://www.youtube.com/watch?v=t4h247PPOrY
Antonio Elias, VP, CTO, Orbital Sciences, Lecture on Space Transportation

http://www.youtube.com/watch?v=oY3GclS5VUQ

Communications & Telemetry
Antenna Gain

• Isotropic (uniform) radiation of power, $P$, from the center of a sphere of radius, $r$
• Power per unit area (power density) of the sphere’s surface

$$p = \frac{P}{4\pi r^2}$$

• Power received from isotropic radiator over area, $S$

$$P_S = Sp$$

$\psi$ = beamwidth half-angle

Antenna Gain

• Power received over area, $S$, if all power is focused uniformly on that area by antenna with gain, $G$

$$P_S = GSp_S = P$$

Power density in $S$ with idealized focused antenna

$$p_S = \frac{P}{GS}$$

• Idealized antenna gain

$$G = \frac{P}{Sp_S} = \frac{4\pi r^2}{S}$$
**Relationship of Antenna Area and Signal Wavelength to Antenna Gain**

**Effective antenna gain (transmitting or receiving)**

\[
G_{\text{eff}} = \frac{4\pi A_{\text{eff}}}{\lambda^2}
\]

- \( c = \text{speed of light} \approx 3 \times 10^8 \text{ m / s} \)
- \( f = \text{carrier signal frequency, Hz} \)
- \( A_{\text{eff}} = \text{effective antenna area, m}^2 \)
- \( \lambda = \text{carrier signal wavelength, m} \)
  \[= c / f\]

**Relationship of Antenna Area and Signal Wavelength to Antenna Gain**

**Power received from the transmitter**

\[
P_r = p_r A_r = \frac{G_i P_t A_r}{4\pi r^2}
\]

- \( p_r = \text{power density at receiving antenna} \)
- \( A_r = \text{effective area of receiving antenna} \)
- \( G_i = \text{gain of transmitting antenna} \)
- \( P_t = \text{transmitted power} \)
- \( r = \text{distance between transmitting and receiving antennas} \)

**Power ratio**

\[
\frac{P_r(\text{watts})}{P_t(\text{watts})} = \frac{G_i A_r}{4\pi r^2}
\]
Antenna Characteristics

<table>
<thead>
<tr>
<th>Type of Antenna</th>
<th>Typical Gain</th>
<th>Effective Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Isotropic (reference)</td>
<td>1</td>
<td>( \frac{\lambda^2}{4\pi} )</td>
</tr>
<tr>
<td>Halfwave dipole</td>
<td>1.64</td>
<td>( \frac{1.64\lambda^2}{4\pi} )</td>
</tr>
<tr>
<td>Horn</td>
<td>( \frac{10A}{\lambda^2} )</td>
<td>0.81 A</td>
</tr>
<tr>
<td>Axial mode helix ((\pi D \approx \lambda))</td>
<td>( \frac{5L}{\lambda^2} )</td>
<td>( \frac{L\lambda}{2} )</td>
</tr>
<tr>
<td>Parabolic reflector</td>
<td>( \frac{6.9A}{\lambda^2} )</td>
<td>0.55 A</td>
</tr>
<tr>
<td>Broadside array (ideal)</td>
<td>( \frac{4\pi A}{\lambda^2} )</td>
<td>A</td>
</tr>
</tbody>
</table>

Typical Antenna Pattern

- Gain vs. angle from boresight axis (2-D)
- \( G_{\text{eff}} \) is average gain over beamwidth
- Beamwidth variously defined as \(-3 \text{ dB} \) cone angle or half-angle
Electric and Magnetic Fields of a Dipole Antenna

characteristics of Typical Spacecraft Antennas

<table>
<thead>
<tr>
<th>Type</th>
<th>Frequency Band (GHz)</th>
<th>Gain (dBi)</th>
<th>Beamwidth (deg)</th>
<th>Mass (kg)</th>
<th>Satellite</th>
<th>Size (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quad Helix</td>
<td>L (1.5)</td>
<td>16–19</td>
<td>18</td>
<td>1.8</td>
<td>Intelsat-V</td>
<td>0.4 x 0.4 x 0.47</td>
</tr>
<tr>
<td>Conical Log Spiral</td>
<td>S (2.2)</td>
<td>0–3</td>
<td>220</td>
<td>1.2</td>
<td>FLTSATCOM</td>
<td>0.7 dia</td>
</tr>
<tr>
<td>Parabola (fixed)</td>
<td>S (1.7)</td>
<td>16–19</td>
<td>18</td>
<td>3.9</td>
<td>GOES I, J, K</td>
<td>0.3 dia, 0.65L</td>
</tr>
<tr>
<td>Horn</td>
<td>C (4)</td>
<td>16–19</td>
<td>18</td>
<td>3.1</td>
<td>Intelsat-V</td>
<td>2.4 dia</td>
</tr>
<tr>
<td>Parabola w/ Feed Array</td>
<td>C (4)</td>
<td>21–25</td>
<td>*</td>
<td>29.4</td>
<td>Intelsat-V</td>
<td>1.56 dia</td>
</tr>
<tr>
<td>Parabola w/ Feed Array</td>
<td>C (6)</td>
<td>21–25</td>
<td>*</td>
<td>15.2</td>
<td>Intelsat-V</td>
<td>1.1 dia</td>
</tr>
<tr>
<td>Parabola—Steerable</td>
<td>Ku (11)</td>
<td>36</td>
<td>1.6</td>
<td>5.8</td>
<td>Intelsat-V</td>
<td>1.7 dia</td>
</tr>
<tr>
<td>Parabola w/ Feed Array</td>
<td>Ku (20/30)</td>
<td>45–52</td>
<td>*</td>
<td>47.1</td>
<td>SUPERBIRD</td>
<td>1.7 dia</td>
</tr>
</tbody>
</table>

* Beams shaped to illuminate specific land masses

\[
\text{Gain(dBi)} \triangleq 10 \log \frac{\text{Antenna Gain}}{\text{Isotropic Antenna Gain}}
\]
Alternative Expressions for Power Ratio

\[
\frac{P_r}{P_t} = \frac{G_t A_r}{4\pi r^2} = \frac{A_t A_r}{(\lambda r)^2} = \frac{A_t A_r f^2}{(cr)^2} = \frac{G_t G_r \lambda^2}{4\pi r^2} = \frac{G_r A_t}{4\pi r^2}
\]

Power ratio in decibels

\[
10 \log_{10} \left( \frac{P_r}{P_t} \right) (dB) = G_t (dB) + 10 \log_{10} A_r (dB) - 10 \log_{10} 4\pi (dB) - 20 \log_{10} r (dB)
\]

Detected Power

- Receiver’s detected power includes components from
  - transmitter’s carrier signal
  - information signal
  - noise

\[
\frac{P_r}{P_t} (dB) = \left( \frac{P_r}{P_t} \right)_{\text{ideal}} (dB) - \text{Absorption}(dB) - \text{Rainfall}(dB) \\
\pm \text{Multipath}(dB) - \text{Cross Polarization}(dB)
\]

\[
P_r = P_{\text{carrier}} + P_{\text{information}} \approx P_{\text{carrier}} \\
P_d = P_r + P_n
\]
Noise Sources

- Receiver thermal and “front end” noise
- Atmospheric, cosmic, solar, and man-made noise

\[ P_n = P_{n_{\text{receiver}}} + P_{n_{\text{atmosphere}}} + P_{n_{\text{solar}}} + P_{n_{\text{cosmic}}} + P_{n_{\text{man-made}}} \]

Receiver Noise

Power and temperature

\[ P_n = kT W \text{ (watts)} \]
\[ T = 290 \left(10^{NF(dB)/10} - 1\right) \]
\[ = 290(F - 1) \]

- \( k = \) Boltzmann’s constant = \(1.38 \times 10^{-23}\) \(\text{W} \cdot \text{s}/\text{K}\)
- \( T = \) effective receiver temperature, \(\text{oK}\)
- \( W = \) bandwidth, \(\text{Hz}\)
- \( NF = \) receiver noise figure
- \( F = \) receiver noise factor

Power density

\[ N_o = \frac{P_n}{W} = kT \text{ (watts} / \text{Hz)} \]
Receiver Noise

- Noise proportional to \((\text{wavelength})^n\) or \(1/(\text{frequency})^n\)

Solar Noise

- Noise proportional to \((\text{wavelength})^n\) or \(1/(\text{frequency})^n\)
Cosmic and Atmospheric Noise

\[ P_n \propto \lambda^n \]
\[ \propto 1/f^n \]

Signal-to-Noise Ratio and Information Content

\[ S/N = \frac{P_r (\text{watts})}{P_n (\text{watts})} \]

\[ P_r (dB) = 10 \log \left( \frac{P_r (\text{watts})}{1 \text{ watt}} \right) \]

\[ \frac{S}{N} (dB) = P_r (dB) - P_n (dB) \]

Channel capacity

\[ C (\text{bits} / s) = W \log_2 \left( \frac{S + N}{N} \right) \]
\[ = W \log_2 \left( \frac{S}{N} + 1 \right) \]

\[ W = \text{bandwidth, Hz} \]
Information Bandwidth

\[ f_c = \text{carrier frequency}, \text{Hz} \]
\[ W = \Delta f = f_2 - f_1 = \text{information signal bandwidth}, \text{Hz} \]

- Low-frequency information signal superimposed on (i.e., modulates) high-frequency carrier radio signal for transmission

Information signal formats
- Analog (continuous)
- Digital (discrete)
- Digitized analog (i.e., A/D conversion)

Power spectral density of transmitted signal

Signal-to-Noise Ratio per Bit, \( E_b/N_o \)

\[ E_b : \text{energy per bit} \]
\[ N_o : \text{noise power spectral density} \]

\[ \frac{E_b}{N_o} = \frac{S}{N} \frac{W}{R} \]

- \( S = \text{received signal power} \)
- \( N = \text{received noise power} \)
- \( W = \text{bandwidth of receiver} \)
- \( R = \text{data bit rate} \)

How would you express this in decibels?
Link Budget for a Digital Data Link

\[
\frac{E_b}{N_o} = \frac{S}{W} = \frac{P_t L_l G_t L_s L_a G_r}{k T_s R}
\]

Link budget design goal is to achieve satisfactory \(E_b/N_o\) by choice of link parameters

- \(P_t =\) transmitter power
- \(L_l =\) transmitter – to – antenna line loss
- \(G_t =\) transmit antenna gain
- \(L_s =\) space loss
- \(L_a =\) transmission path loss
- \(G_r =\) receive antenna gain
- \(k =\) Boltzmann’s constant
- \(T_s =\) system noise temperature

… in decibels?

Typical Spacecraft System Noise Temperature

<table>
<thead>
<tr>
<th>Noise Temperature</th>
<th>Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Downlink</td>
</tr>
<tr>
<td></td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Antenna Noise (K)</strong></td>
<td>150</td>
</tr>
<tr>
<td><strong>Line Loss (dB)</strong></td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Line Loss Noise (K)</strong></td>
<td>35</td>
</tr>
<tr>
<td><strong>Receiver Noise Figure (dB)</strong></td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Receiver Noise (K)</strong></td>
<td>36</td>
</tr>
<tr>
<td><strong>System Noise (K)</strong></td>
<td>221</td>
</tr>
<tr>
<td><strong>System Noise (dB-K)</strong></td>
<td>23.4</td>
</tr>
</tbody>
</table>
Free-Space Laser Communication

• Diffraction limit of electro-magnetic beam is proportional to \( \lambda/d \)
  • \( \lambda = \) Wavelength
  • \( d = \) aperture (diameter) of beam source
• Radio frequency wavelengths: \( cm - m \)
• Optical wavelengths: \( \mu m \)
• Up to \( 10^6 \) less beam spread for optical communication

*Lesh, JPL, 1999*
Optical Communication Advantage Compared to Ka-Band RF
(One-Way Pluto example, same power input)

<table>
<thead>
<tr>
<th>dB</th>
<th>Factor</th>
<th>Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>Data Rate Increase</td>
<td>4.9 kbs vs. 270 bps</td>
</tr>
<tr>
<td>26</td>
<td>Smaller Spacecraft Aperture</td>
<td>10 cm vs. 2 m</td>
</tr>
<tr>
<td>4</td>
<td>Less Transmitted Power Required</td>
<td>1 W vs. 2.7 W</td>
</tr>
<tr>
<td>7</td>
<td>Lower Transmitter Efficiency</td>
<td>5% vs. 28%</td>
</tr>
<tr>
<td>2</td>
<td>Lower System Efficiencies</td>
<td>24% vs. 40%</td>
</tr>
<tr>
<td>3</td>
<td>Atmospheric Loss</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>Smaller Ground Station</td>
<td>10 m vs. 34 m</td>
</tr>
</tbody>
</table>

Lesh, JPL, 1999

Good News/Bad News for Optical Communication

• **Good news**
  • Higher bit rates possible
  • Optical beams are narrower
  • Energy concentrated on receiver

• **Bad News**
  • Optical beams are narrower
  • Narrow beams must pointed more precisely
  • Must track intended receiver
  • RF may be preferred for acquisition, command, and tracking
  • Effects of cloud cover

Lesh, JPL, 1999
LADEE Lunar LaserCom Space Terminal

LADEE LaserCom Components
Deep Space Network

- Radar tracking (range, elevation, and azimuth)
- Radiated signal power drops off as $1/r^2$
- Reflected return signal power drops off as $1/r^2$
- “Skin track” return signal power drops off as $1/r^4$
- Beacon (or transponder) on cooperative target
  - Receives radiated signal
  - Re-transmits fresh signal
    - Known time delay
    - Different frequency
  - Return signal power drops off as $1/r^2$

Deep Space Network Coverage

Goldstone 70-m Antenna

Moon is 10x further away than GEO

Geosynchronous orbit

30,000 km from Earth

Low Earth Orbit (600 km)
Next Time:

Spacecraft Power & Thermal Control
[Understanding Space] Sec 13.2, 13.3
Social & Political Aspects of Space Flight:
[Societal Impact of Space Flight, NASA-SP-4801] Ch 4, 8, and 9

Supplemental Material
Communications Geometry

- Ground station communication and tracking limited by its minimum elevation angle, $\gamma$
- Fixed (non-steerable) antenna must have sufficient beamwidth to transmit or receive
- Antenna gains and radiated power must be adequate, given slant range and noise environment

$$R = \sqrt{(R_e + h)^2 - R_e^2 \cos^2 \theta - R_e \sin \theta}$$
$$\alpha = \cos^{-1} \left( \frac{R_e \cos \theta}{R_e + h} \right) - \theta$$

Beamwidth Coverage

- Broad or narrow coverage may be desired

$$\psi(\text{cone}) \approx \frac{21}{fd} \text{deg}$$
$$f = \text{carrier signal frequency}, \text{GHz}$$
$$d = \text{reflector diameter}, \text{m}$$
Fig. 34—One-way radio-communication calculation chart. Given 1-mi bandwidth, 10-db noise figure, 20-db signal-to-noise ratio, 10-watts power output, 20-db total antenna gain, and 250-mc operating frequency, to find receiver noise level, receiver input signal level, and communication range, procedure is as follows: (1) project line connecting points on Scales 1 and 2 to point on Scale 3; (2) read receiver noise level (+104 dbm); (3) from this point on Scale 3 project line through Scale 4 to Scale 5 and read receiver-input signal level (-86 dbm or 14 mg); (4) at intersection of Scale 7 and the line drawn between points on Scales 9 and 5, read path loss (124 db from isotropic antenna); (5) on Scale 7 add antenna gains and read true path loss (144 db); (6) project line from Scale 8 through Scale 7 and read communications range on Scale 6 (1000 miles).
Atmospheric Attenuation, Multipath, and Ionospheric Effects on Space-Earth Communication

\[
\frac{P_f}{P_i} (dB) = \frac{P_f}{P_{\text{ideal}}} (dB) - \text{Absorption}(dB) - \text{Rainfall}(dB)
\pm \text{Multipath}(dB) - \text{Cross Polarization}(dB)
\]

Analog Amplitude, Frequency, and Phase Modulation of Carrier Signal

\[
m(t) = \cos(\omega_m t) = \cos(2\pi f_m t)
\]

\[
V = V_c (1 + m \cos(\omega_m t)) \cos(\omega_c t + \phi)
\]

\[
\beta = \text{modulation index}
\]

\[
\Delta f = \text{frequency deviation}
\]

\[
\beta = \text{modulation index} \text{ or 'phase deviation'}
\]
Digital Amplitude-, Frequency-, and Phase-Shift Modulation of Carrier Signal

Bit Error Rate vs. $E_b/N_0$

- Goal is to achieve lowest bit error rate (BER) with lowest $E_b/N_o$
- Implementation losses increase required $E_b/N_0$
- Link margin is the difference between the minimum and actual $E_b/N_0$
- BER can be reduced by error-correcting codes
  - Number of bits transmitted is increased
  - Additional check bits allow errors to be detected and corrected
### Communications Carrier Frequencies

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>Frequency Range (GHz)</th>
<th>Service</th>
<th>Downlink Power Flux Density Limit (dBW/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UHF</td>
<td>0.2 – 0.45</td>
<td>Military</td>
<td>—</td>
</tr>
<tr>
<td>L</td>
<td>1.635 – 1.66</td>
<td>Maritime/Nav Telephone</td>
<td>—1.44/4 kHz</td>
</tr>
<tr>
<td>S</td>
<td>2.65 – 2.69</td>
<td>Broadcast, Telephone</td>
<td>—137/4 kHz</td>
</tr>
<tr>
<td>C</td>
<td>5.9 – 6.4</td>
<td>Domestic, Comsat</td>
<td>—142/4 kHz</td>
</tr>
<tr>
<td>X</td>
<td>7.9 – 8.4</td>
<td>Military, Comsat</td>
<td>—142/4 kHz*</td>
</tr>
<tr>
<td>Ku</td>
<td>14.0 – 14.5</td>
<td>Domestic, Comsat</td>
<td>—138/4 kHz</td>
</tr>
<tr>
<td>Ka</td>
<td>27.5 – 31.0</td>
<td>Domestic, Comsat</td>
<td>—105/1 MHz</td>
</tr>
<tr>
<td>SHF/EHF</td>
<td>43.5 – 45.5</td>
<td>Military, Comsat</td>
<td>—</td>
</tr>
<tr>
<td>V</td>
<td>V</td>
<td>Satellite Crosslinks</td>
<td>—135/1 MHz</td>
</tr>
</tbody>
</table>

*No limit in exclusively military band of 7.70–7.75 GHz.

### Typical Command and Telemetry Characteristics

<table>
<thead>
<tr>
<th>Network</th>
<th>Command (Uplink)</th>
<th>Telemetry (Downlink)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Freq. (GHz)</td>
<td>Data Rate (bps)</td>
</tr>
<tr>
<td>Air Force SCN</td>
<td>1.76–1.84</td>
<td>1,000 2,000</td>
</tr>
<tr>
<td>(SGLS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NASA DSN</td>
<td>2.025–2.120</td>
<td>1.0–2,000</td>
</tr>
<tr>
<td></td>
<td>7.145–7.190</td>
<td></td>
</tr>
<tr>
<td>Intelsat/</td>
<td>5.92–6.42</td>
<td>100–250</td>
</tr>
<tr>
<td>COMSAT</td>
<td>14.0–14.5</td>
<td>100–250</td>
</tr>
<tr>
<td>TDRS*** (user</td>
<td>2.1064</td>
<td>*MA 10 kbps max</td>
</tr>
<tr>
<td>satellite</td>
<td>max 300k max</td>
<td></td>
</tr>
<tr>
<td>altitude below</td>
<td>2.025–2.120</td>
<td>25M max</td>
</tr>
<tr>
<td>12,000 km)</td>
<td>**SA 13.775</td>
<td></td>
</tr>
</tbody>
</table>

*MA—Multiple Access, up to 20 users simultaneously
**SA—Single Access
***Frequencies to and from user satellite
## Typical Communication Satellite Transponder Characteristics

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Band</th>
<th>Transponder Bandwidth (MHz)</th>
<th>Number Transponders</th>
<th>Total Relay Bandwidth (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intelsat-V</td>
<td>C</td>
<td>36/41, 72/77, 241</td>
<td>4/1, 12/4, 2</td>
<td>2,137</td>
</tr>
<tr>
<td></td>
<td>Ku</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DSCS-III</td>
<td>X</td>
<td>50, 60, 85</td>
<td>1, 4, 1</td>
<td>375</td>
</tr>
<tr>
<td>Globalstar</td>
<td>L, S, C</td>
<td>16.5</td>
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