## Professional Development Short Course On:

# Satellite Communications Design & Engineering

## Instructor:

Christopher DeBoy

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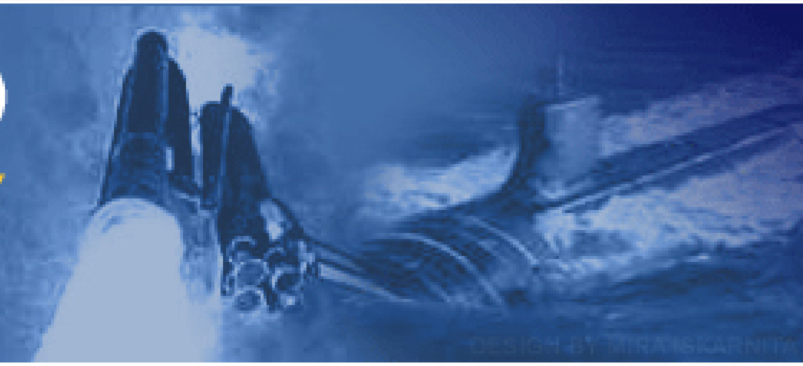


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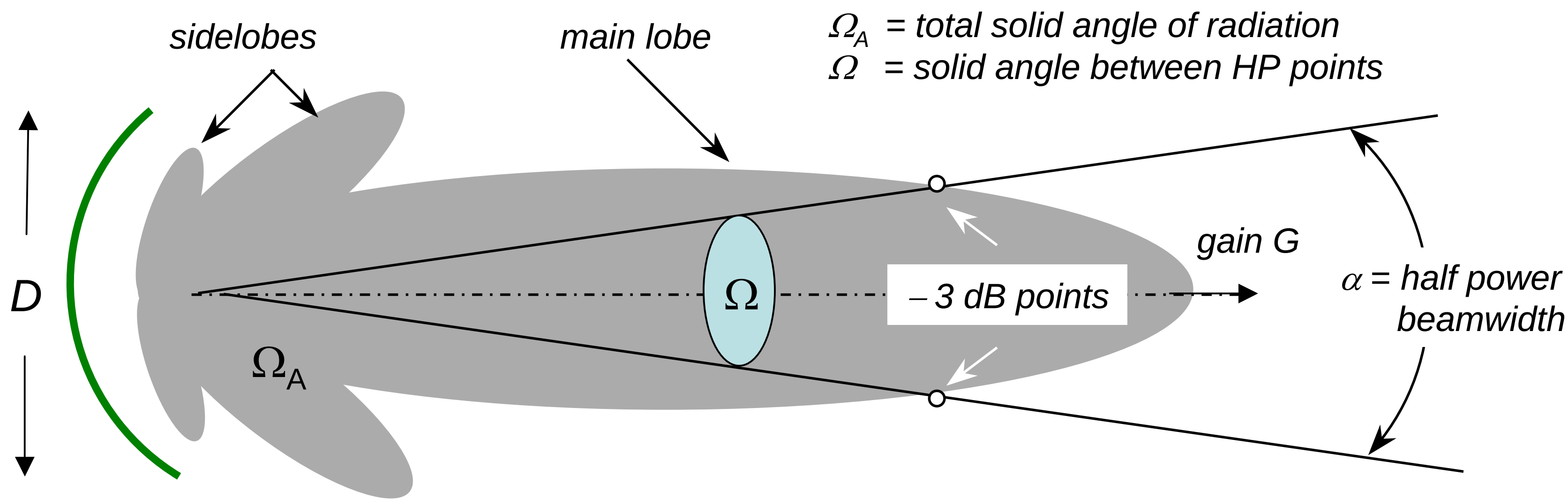
# Outline

# The RF Link

**(Excerpt)**

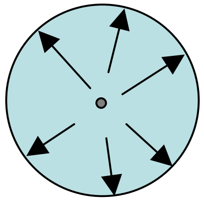
# Antenna pattern, beamwidth, and gain




Beamwidth shows size of beam.

$$\mathrm{HPBW} = \alpha = k\,\frac{\lambda}{D} = 70^\circ\,\frac{\lambda}{D}$$ where $k$ = antenna taper factor

An isotropic antenna radiates equally in all directions like a light bulb



$\Omega = 4\pi$

Gain shows relative strength of radiation. The maximum (boresight) gain is

$$G = \eta^* \frac{4\pi}{\Omega_A} = \eta' \frac{4\pi}{\Omega} = \frac{29{,}000}{\alpha^2} = \eta \frac{4\pi}{\lambda^2} A = \eta \left(\frac{\pi D}{\lambda}\right)^2$$ where $\eta^*$, $\eta'$, $\eta$ = measures of antenna efficiency

Gain and beamwidth are linked: As the gain increases, the beamwidth decreases, and vice versa.

# Example:  Earth terminal antenna

Ku band downlink frequency
*f* = 12 GHz

$$\lambda = \frac{c}{f} = \frac{3\times10^{8}\ \text{m/s}}{12\times10^{9}\ \text{Hz}} = 0.025\ \text{m}$$

$$\text{HPBW} = \alpha = 70^\circ\frac{\lambda}{D} = 70^\circ\,\frac{0.025\ \text{m}}{5.0\ \text{m}} = 0.35^\circ$$

$$G = \eta\left(\frac{\pi\,D}{\lambda}\right)^{2} = 0.60\left(\frac{\pi\,5.0\ \text{m}}{0.025\ \text{m}}\right)^{2} = 237{,}000$$

$$[G] = 10\,\log_{10}(237{,}000) = 53.7\ \text{dB}$$

Prime Focus Feed; 5 meter reflector; Tx and Rx
C-Band gain 46 dB; Beamwidth = 1$^{o}$
Ku-Band gain 54 dB; Beamwidth = 0.4$^{o}$

# Equivalent isotropic radiated power (EIRP)

The equivalent isotropic radiated power (EIRP) is the transmit power of a hypothetical antenna radiating equally in all directions (like a light bulb) so as to have the same power flux density over the coverage area as the actual antenna.

The power flux density of the actual antenna is

$$\Phi = \frac{P}{S} = \frac{\eta^* P_{in}}{\Omega_A d^2} = \eta^* \frac{4\pi}{\Omega_A} \frac{P_{in}}{4\pi d^2} = G_t \frac{P_{in}}{4\pi d^2}$$

where $\eta^*$ is the antenna power loss efficiency, $P = \eta^* P_{in}$ is the transmitted power, $S$ is the total coverage area at distance $d$, $\Omega_A$ is the antenna beam solid angle, and $G_t = \eta^* (4\pi / \Omega_A)$ is the transmit gain.

By the definition of EIRP

$$\Phi = \frac{\mathrm{EIRP}}{4\pi d^2}$$

Therefore,

$$\mathrm{EIRP} = G_t \, P_{in}$$

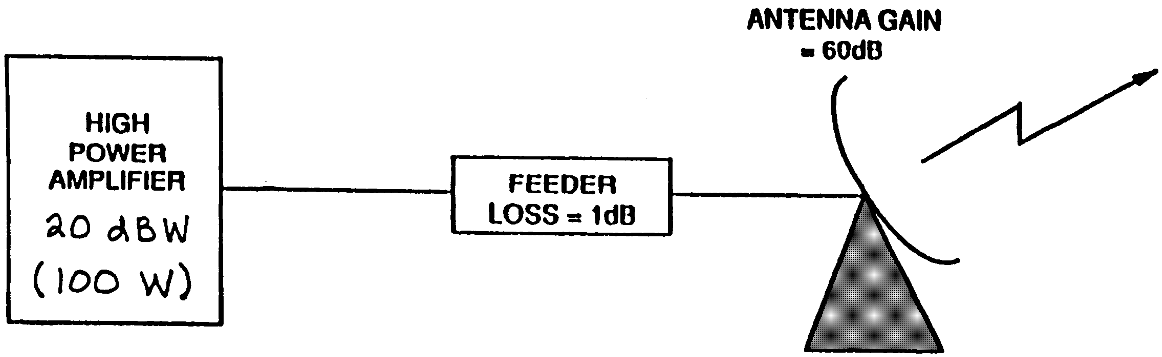
The EIRP is the product of the antenna transmit gain and the power applied to the *input* terminals of the antenna. The antenna efficiency $\eta^*$ is absorbed in the definition of gain.

# Example 1

| *numeric form* | *logarithmic (dB) form* |
| --- | --- |
| $G_t = 100$ | $[G_t] = 10 \log_{10}(100) = 20.0$ dB |
| $P_{in} = 50$ W | $[P_{in}] = 10 \log_{10}$ (50 W) = 17.0 dBW |
| EIRP = $G_t\, P_{in}$ | [EIRP] = $[G_t] + [P_{in}]$ |
| = (100)(50 W) | = 20.0 dB + 17.0 dBW |
| = 5000 W | = 37.0 dBW |

$10 \log_{10}$(5000 W) = 37.0 dBW

# Example 2




$[P_{\mathrm{HPA}}] = 10 \log_{10}(100\ \mathrm{W}) = 20\ \mathrm{dBW}$

$[P_{\mathrm{in}}] = [P_{\mathrm{HPA}}] - [L] = 20\ \mathrm{dBW} - 1\ \mathrm{dB} = 19\ \mathrm{dBW}$

$[\mathrm{EIRP}] = [G_t] + [P_{in}] = 60\ \mathrm{dB} + 19\ \mathrm{dBW} = 79\ \mathrm{dBW}$

# Figure of Merit ($G$ / $T$)

The ratio of the receive antenna gain $G$ to the total system temperature $T$ is called the "figure of merit."

$$[\,G\,/\,T\,] = [\,G\,] - [\,T\,] \qquad \text{(dB/K)}$$

where

$[\,G\,]$ = receive antenna gain (dB)

$[\,T\,]$ = total system temperature (dBK)

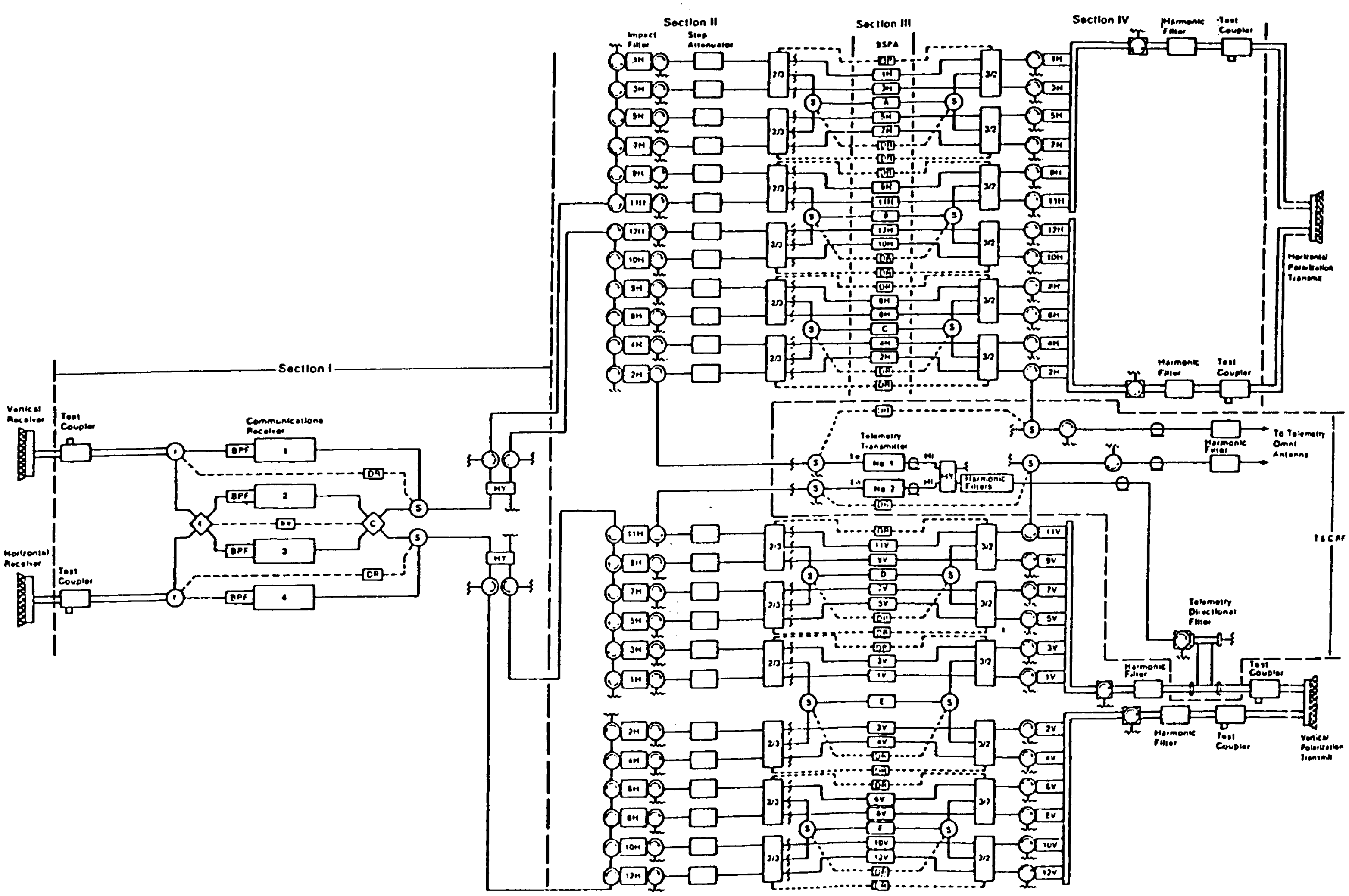
The figure of merit is independent of the point where it is calculated. However, the gain and system temperature must be specified at the same point.

Example: Suppose the antenna gain is 53.7 dB and the system temperature is 150 K. Then

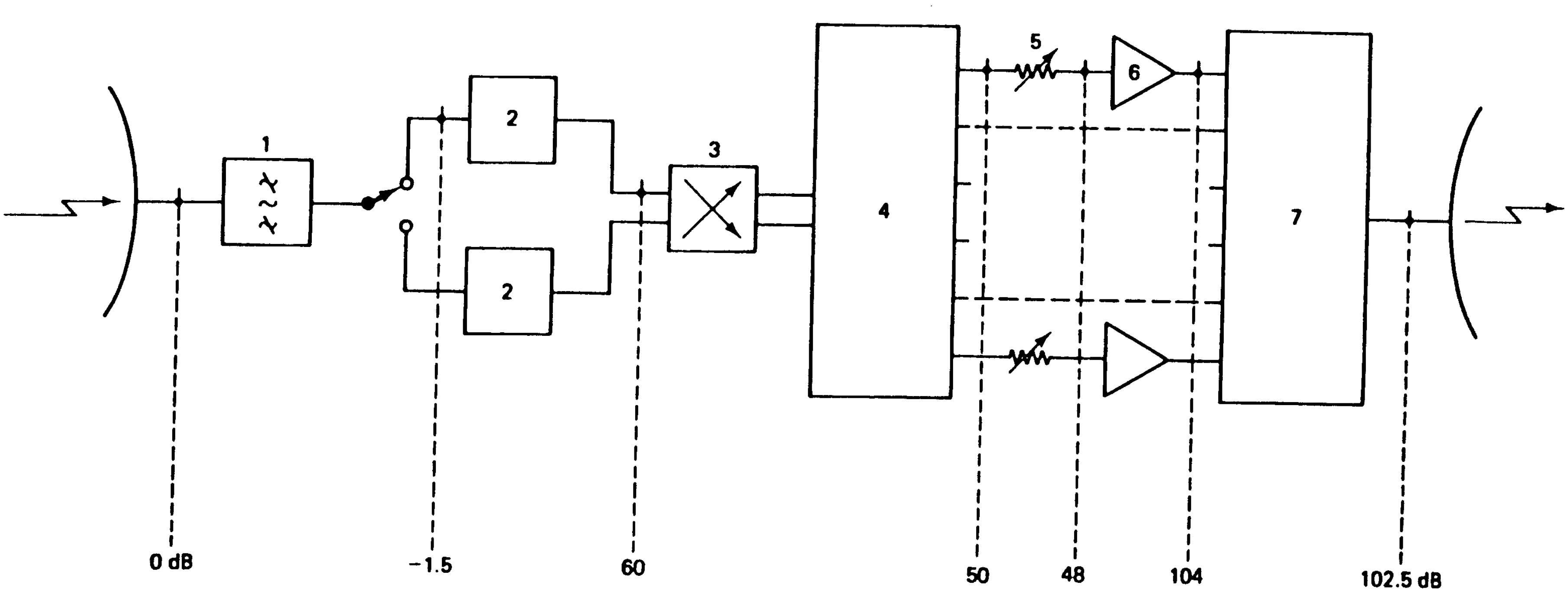
$$[\,T\,] = 10\log_{10}(150\text{ K}) = 21.7\text{ dBK}$$

$$[\,G\,/\,T\,] = [\,G\,] - [\,T\,] = 53.7\text{ dB} - 21.7\text{ dBK} = 32.0\text{ dB/K}$$

# Satellite communications payload architecture

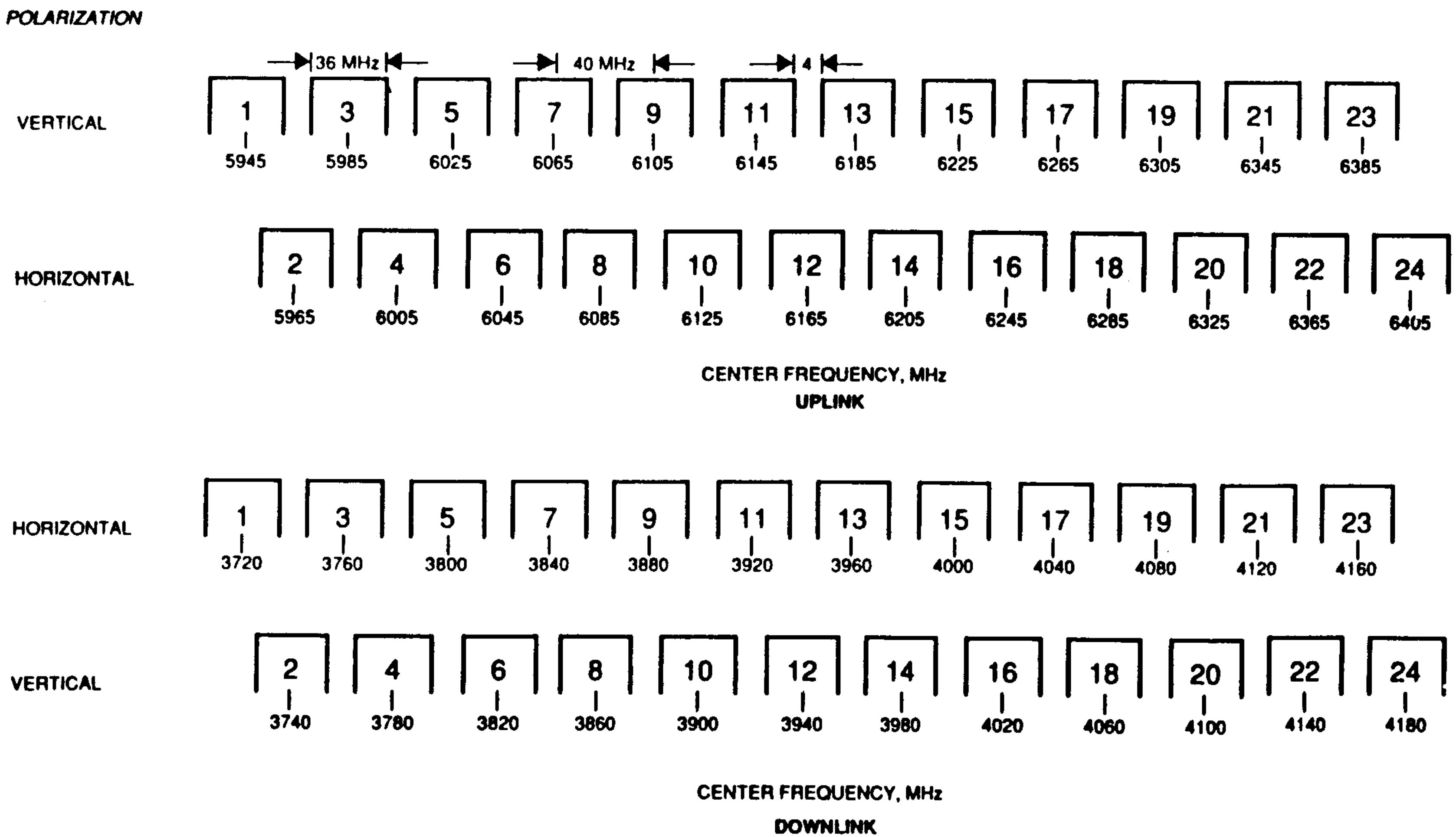


# Transponder




0 dB reference level
1 input filter
2 wideband receiver
3 3 dB coupler
4 demultiplexer
5 attenuator (lower position)
6 amplifier
7 multiplexer

# Satellite transponder frequency plan (C-band)



# Typical satellite data

## Telstar 5 97º W C/Ku band

Began service: 7/ 97

Station-keeping ± 0.05 degrees
Mission Life 12 years

Transponders: 24 C-band @ 36 MHz
4 Ku-band @ 54 MHz
24 Ku-band @ 27 MHz

Coverage: Continental US, Alaska, Hawaii, Puerto Rico, the Caribbean, and into Canada and Latin America.

Markets: Strong broadcast and syndication neighborhood anchored by ABC and FOX; host to SNG, data, business television, Internet, direct-to-home programming and digital data applications

| Orbital Location | Transponders | Useable Bandwidth | Power |
|---|---|---|---|
| 97 degrees W | 24 C-band | 36 MHz | 20 W nominal |
| | 4 Ku-band | 54 MHz | 100 W nominal |
| | 24 Ku-band | 27 MHz | 100 W nominal |

**Saturation Flux Density - Typical CONUS**
-71 to -92 (dBW/m²) at C-band adjustable in 1 dB steps

-75 to -96 (dBW/m²) at Ku-band adjustable in 1 dB steps

**Polarization**
Orthogonal linear polarization at C-band and Ku-band.

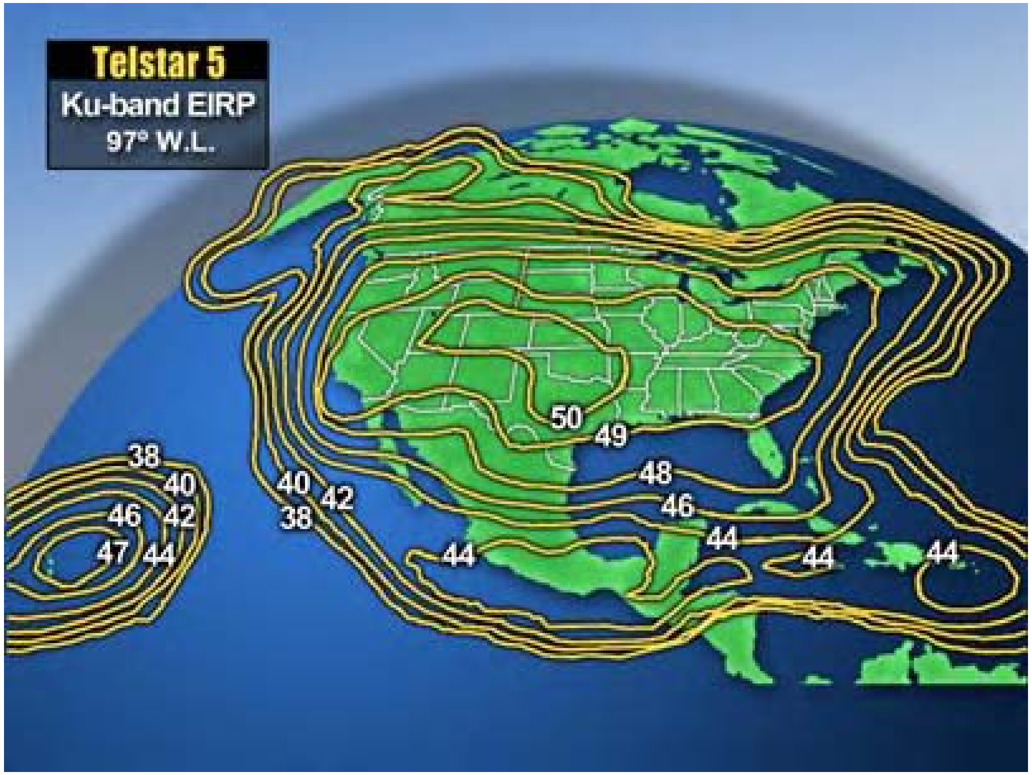
**Frequency Band**
4/6 GHz and 12/14 GHz

**Ku-band Optional "Automatic Level Control" Mode**
Mitigates the effects of uplink rain fade by maintaining the transponder at a specific fixed operating point between saturation and 8 dB input backoff.

| EIRP (dBW) | C-band | Ku-band |
|---|---|---|
| CONUS | 38.8 | 48.3 |
| Alaska | 33.7 | 39.1 |
| Hawaii | 33.8 | 46.4 |
| Puerto Rico/U.S. Virgin Islands | 34.0 | 44.9 |
| Mexico | 35.9 | 43.6 |
| Southern Canada | 37.0 | 44.3 |
| Caribbean | 34.3 | 43.4 |

| G/T (dB/K) | C-band | Ku-band |
|---|---|---|
| CONUS | 0.4 | 1.2 |
| Alaska | -8.2 | -5.9 |
| Hawaii | -5.2 | 0.6 |
| Puerto Rico/U.S. Virgin Islands | -3.7 | 0.7 |
| Mexico | -3.5 | -3.5 |
| Southern Canada | -2.3 | -0.6 |
| Caribbean | -3.5 | -2.3 |

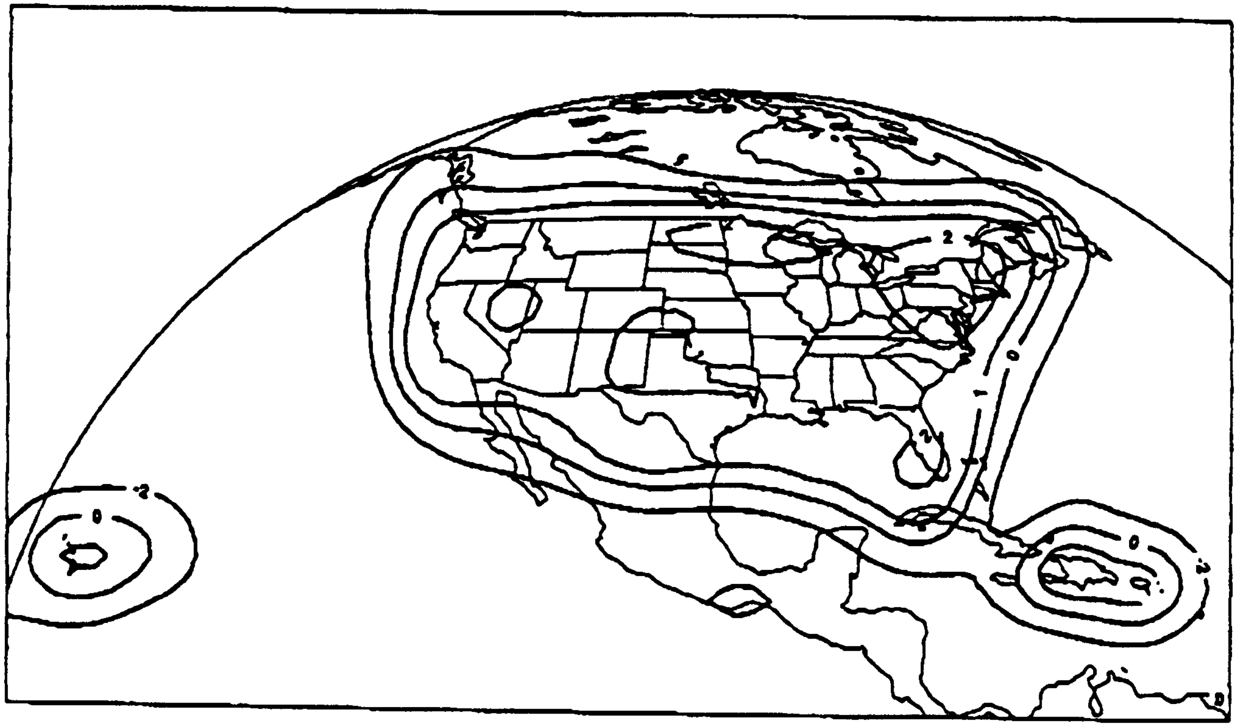
# Satellite EIRP footprint




$P$ = 100 W $\quad$ [ $P$ ] = 20 dBW $\quad$ [ $G$ ] = 30 dB

[ EIRP ] = [ $G$ ] + [ $P$ ] = 30 dB + 20 dBW = 50 dBW (COC)

# Satellite Figure of Merit *G / T*



$T$ = 630 K    [ $T$ ] = 28 dBK    [ $G$ ] = 30 dB

[ $G$ / $T$ ] = [ $G$ ] – [ $T$ ] = 30 dB – 28 dBK = 2 dB/K (COC)

# Earth-satellite geometry

Telstar 5 97º W C / Ku band

| City/Country | Latitude | W Longitude | Azimuth | Elevation |
|---|---|---|---|---|
| Anchorage, AK/USA | 61.22 | 149.90 | 123.52 | 8.3 |
| Boston, MA/USA | 42.21 | 71.03 | 215.82 | 34.6 |
| Calgary/Canada | 51.08 | 114.08 | 158.45 | 29.3 |
| Dallas, TX/USA | 32.46 | 96.47 | 180.37 | 52.2 |
| Guatemala City/Guatemala | 14.63 | 90.52 | 204.71 | 71.2 |
| Halifax/Canada | 44.65 | 63.60 | 223.21 | 28.8 |
| Havana/Cuba | 23.12 | 82.42 | 213.52 | 58.3 |
| Honolulu, HI/USA | 21.32 | 157.83 | 101.44 | 18.8 |
| Houston, TX/USA | 29.45 | 95.21 | 183.28 | 55.6 |
| Jacksonville, FL/USA | 30.19 | 81.39 | 208.53 | 50.9 |
| Los Angeles, CA/USA | 34.03 | 118.14 | 145.36 | 44.4 |
| Merida/Mexico | 20.97 | 89.62 | 199.81 | 64.0 |
| Mexico City/Mexico | 19.42 | 99.17 | 173.65 | 67.1 |
| Miami, FL/USA | 25.46 | 80.11 | 214.78 | 54.8 |
| Nassau/Bahamas | 25.08 | 77.33 | 220.17 | 53.3 |
| New York, NY/USA | 40.43 | 74.01 | 213.10 | 37.6 |
| Reno, NV/USA | 39.53 | 119.82 | 146.53 | 38.5 |
| San Francisco, CA/USA | 37.46 | 122.25 | 142.19 | 39.1 |
| San Juan/Puerto Rico | 18.48 | 66.13 | 242.07 | 48.8 |
| Seattle, WA/USA | 47.60 | 122.33 | 147.34 | 30 |
| Toronto/Canada | 43.70 | 79.42 | 204.71 | 36.6 |
| Vancouver/Canada | 49.22 | 123.10 | 147.10 | 28.3 |
| Washington, DC/USA | 38.53 | 77.02 | 210.99 | 40.7 |

Example: Earth terminal in Los Angeles

$$\cos\gamma = \cos\phi\cos\Delta\lambda$$
$$= \cos(34.03°)\cos(118.14° - 97.0°)$$
$$= 0.7730$$

$$\gamma = 39.38°$$

$$\sin Az = \frac{\sin\Delta\lambda}{\sin\gamma}$$
$$= \frac{\sin(118.14° - 97.0°)}{\sin(39.38°)}$$
$$= 0.5685$$

$$Az = 180° - 34.64° = 145.36°$$

$$\tan\theta = \frac{\cos\gamma - R_E/r}{\sin\gamma}$$
$$= \frac{\cos(39.38°) - (6378\text{ km})/(42{,}164\text{ km})}{\sin(39.38°)}$$
$$= 0.9799$$

$$\theta = 44.42°$$

# Free space loss

The free space loss takes into account that electromagnetic waves spread out into spherical wavefronts as they propagate through space due to diffraction.

$$L_s = \left( \frac{4\pi\, d}{\lambda} \right)^2 = \left( \frac{4\pi\, d\ f}{c} \right)^2$$

$$[L_s] = 10\log_{10}\left( \frac{4\pi d}{\lambda} \right)^2 = 20\log_{10}\left( \frac{4\pi d}{\lambda} \right)$$

For a geostationary satellite, the free space loss is on the order of 200 dB (or a factor of $10^{20}$).

The received power at the earth terminal is typically on the order of tens of *pico*watts.

# Example

*Problem:* Determine the free space loss for a Ku band downlink between Telstar 5 at 97° W Longitude and Los Angeles if the frequency is 12 GHz and the angle of elevation is 44.4°.

*Solution:* The wavelength is

$$\lambda = \frac{c}{f} = \frac{3\times10^{8}\ \text{m/s}}{12\times10^{9}\ \text{Hz}} = 0.025\ \text{m}$$

The slant range is

$$d = \sqrt{r^2 - (R_E \cos\theta)^2} - R_E \sin\theta$$

$$= \sqrt{(42{,}164\ \text{km})^2 - (6378\ \text{km}\times\cos 44.4°)^2} - 6378\ \text{km}\times\sin 44.4°$$

$$= 37{,}453\ \text{km}$$

*r* = orbit radius

$R_E$ = Earth's radius

$\theta$ = elevation angle

Thus

$$L_s = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi\times 37{,}453{,}000\ \text{m}}{0.025\ \text{m}}\right)^2 = 3.544\times10^{20}$$

$$[L_s] = 10\log_{10}(3.544\times10^{20}) = 205.5\ \text{dB}$$

# Received carrier power

Received carrier power

$$C = \frac{A_e}{S}\frac{P}{L} = \Phi\, A_e$$

Transmit gain

$$G_t = \eta * \frac{4\pi}{\Omega_A} = \eta * \frac{4\pi\, d^2}{S}$$

Footprint area

$$S = \eta * \frac{4\pi\, d^2}{G_t}$$

Receive gain

$$G_r = \frac{4\pi}{\lambda^2} A_e$$

Receiver equivalent area

$$A_e = G_r \frac{\lambda^2}{4\pi}$$

Received carrier power

$$\boxed{C = \frac{G_r\,(\lambda^2/4\pi)}{4\pi\, d^2/G_t}\frac{P}{\eta *}\frac{1}{L} = \frac{(G_t\, P_{in})\, G_r}{(4\pi\, d/\lambda)^2 L} = \frac{\mathrm{EIRP}\; G_r}{L_s\, L}}$$

Equivalent isotropic radiated power

$$\mathrm{EIRP} = G_t\, P_{in}$$

Free space loss

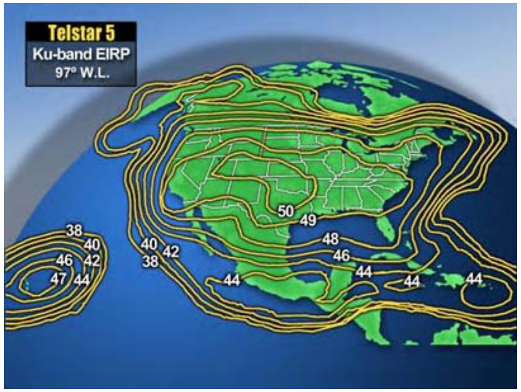
$$L_s = \left(\frac{4\pi\, d}{\lambda}\right)^2$$

# Example

*Problem:* Determine the received carrier power for the Ku band downlink between Telstar 5 and an Earth terminal in Los Angeles if the frequency is 12 GHz and the antenna has an efficiency of 0.60 and a diameter of 5.0 m. Allow a rain attenuation loss of 1.9 dB, a gaseous atmospheric loss of 0.1 dB, and a pointing loss of 0.2 dB.

*Solution:* The satellite EIRP in Los Angeles is 49.2 dBW. At 12 GHz, the antenna gain is 53.7 dB and the free space loss is 205.5 dB. Therefore, the received carrier power is

$$
\begin{aligned}
[C] &= [\mathrm{EIRP}] + [G_r] - [L_s] - [L_r] - [L_a] - [L_p] \\
&= 49.2\ \mathrm{dBW} + 53.7\ \mathrm{dB} - 205.5\ \mathrm{dB} \\
&\quad -1.9\ \mathrm{dB} - 0.1\ \mathrm{dB} - 0.2\ \mathrm{dB} \\
&= -104.8\ \mathrm{dBW}
\end{aligned}
$$




Therefore,

$$C = 10^{-10.48}\ \mathrm{W} = 3.3\times10^{-11}\ \mathrm{W} = 33\ \mathrm{pW}$$

# Noise power

Thermal noise power in bandwidth *B*

$$N = N_0\, B = k_B\, T\, B$$

where the spectral noise density is

$$N_0 = k_B\, T$$

for system temperature *T* and Boltzmann's constant is

$$k_B = 1.381 \times 10^{-23}\ \mathrm{W/K\ Hz} \qquad [k_B] = -228.6\ \mathrm{dBW/K\ Hz}$$

# Link budget equation

Carrier power

$$C = \frac{\mathrm{EIRP}\ G_r}{L_s\ L_r\ L_o}$$

Noise power

$$N = k_B\, T\, B = N_0\, B$$

Carrier to noise ratio

$$\frac{C}{N} = \mathrm{EIRP}\ \frac{G}{T}\ \frac{1}{L_s}\ \frac{1}{L_r}\ \frac{1}{L_o}\ \frac{1}{k_B}\ \frac{1}{B}$$

Carrier to noise density ratio

$$\frac{C}{N_0} = \frac{C}{N}\, B = \mathrm{EIRP}\ \frac{G}{T}\ \frac{1}{L_s}\ \frac{1}{L_r}\ \frac{1}{L_o}\ \frac{1}{k_B}$$

# Link budget equation (continued)

The link budget equation is expressed in logarithmic (dB) form as follows (dB values indicated by brackets):

Uplink

$$[C/N_0] = [\mathrm{EIRP}] + [G/T] - [L_s] - [L_r] - [L_o] - [k_B]$$

at satellite E/S satellite at uplink frequency

Downlink

$$[C/N_0] = [\mathrm{EIRP}] + [G/T] - [L_s] - [L_r] - [L_o] - [k_B]$$

at E/S satellite E/S at downlink frequency

# Combined uplink and downlink

Only thermal noise (Average White Gaussian Noise)

$$\left(\frac{C}{N}\right)_{net}^{-1} = \left(\frac{C}{N}\right)_{up}^{-1} + \left(\frac{C}{N}\right)_{down}^{-1} \qquad \text{(numeric)}$$

Include interference

$$\left(\frac{C}{N}\right)_{net}^{-1} = \left(\frac{C}{N}\right)_{up}^{-1} + \left(\frac{C}{N}\right)_{down}^{-1} + \left(\frac{C}{I}\right)^{-1}$$

Noise power

$$N = N_0\, B$$

$$\frac{C}{N} = \frac{C}{N_0}\,\frac{1}{B}$$

# Power flux density

The EIRP of the uplink Earth station antenna must be adjusted to match an acceptable power flux density (PFD) at the satellite.

$$\mathrm{PFD} = \Phi = \frac{\mathrm{EIRP}}{4\pi d^2}\frac{1}{L_r}\frac{1}{L} = \frac{\mathrm{EIRP}}{L_s\,(\lambda^2/4\pi)}\frac{1}{L_r}\frac{1}{L}$$

$$[\Phi] = [\mathrm{EIRP}] - [4\pi d^2] - [L_r] - [L]$$

or

$$[\Phi] = [\mathrm{EIRP}] - [L_s] - [\lambda^2/4\pi] - [L_r] - [L]$$

# Example

*Problem:* For an uplink between an Earth station in Washington, DC and Telstar 5, the EIRP is 79.0 dBW, the slant range is 37,722 km, the rain attenuation is 5.9 dB, and the antenna pointing loss is 0.2 dB. Determine the power flux density incident on the satellite.

*Solution:*

$$[\Phi] = [\mathrm{EIRP}] - [4\pi d^2] - [L_r] - [L]$$

$$= 79.0\ \mathrm{dBW} - 10\log_{10}\left\{4\pi\,(37{,}722{,}000\ \mathrm{m})^2\right\} - 5.9\ \mathrm{dB} - 0.2\ \mathrm{dB}$$

$$= -89.6\ \mathrm{dBW/m^2}$$

This PFD is within the specifications for Telstar 5.

**Saturation Flux Density - Typical CONUS**

-75 to -96 ($\mathrm{dBW/m^2}$) at Ku-band adjustable in 1 dB steps

**Ku-band Optional "Automatic Level Control" Mode**
Mitigates the effects of uplink rain fade by maintaining the transponder at a specific fixed operating point between saturation and 8 dB input backoff.

# Example link budget

***Signal architecture***

| | | |
|---|---|---|
| Information bit rate | Mbps | 22.5 |
| | dBHz | 73.5 |
| Modulation | | QPSK |
| Coding | | V(7,1/2) |
| Bits per symbol | | 2 |
| Code rate | | 1/2 |
| Percentage of raised cosine filtering | | 20 |
| Noise bandwidth | MHz | 22.5 |
| Occupied bandwidth | MHz | 27.0 |
| BER | | 0.00001 |
| Eb/No (uncoded) | dB | 9.6 |
| Coding gain | dB | 5.1 |
| Eb/No (ideal) | dB | 4.5 |
| Modem implementation loss | dB | 0.5 |
| Eb/No (required) | dB | 5.0 |
| C/No (required) | dBHz | 78.5 |

***Satellite***

| | | |
|---|---|---|
| Name | | Telstar 5 |
| Longitude | deg | 97.0 |
| Transponder bandwidth | MHz | 27.0 |
| EIRP | dBW | 49.2 |
| G/T | dB/K | 2.0 |

# Example link budget (continued)

***Uplink***

***Earth station transmit terminal***

| | | |
|---|---|---|
| City | | Washington |
| Longitude | deg | 77.0 |
| Latitude | deg | 38.5 |
| Earth central angle | deg | 42.7 |
| Elevation angle | deg | 40.8 |
| Slant range | km | 37722 |
| HPA Power | W | 100.0 |
| | dBW | 20.0 |
| Antenna diameter | m | 9.2 |
| Antenna half power beamwidth | deg | 0.16 |
| Antenna efficiency | | 0.55 |
| Antenna transmit gain | dBW | 60.0 |
| Line loss | dB | 1.0 |
| EIRP | dBW | 79.0 |

***Link calculation***

| | | |
|---|---|---|
| Frequency | GHz | 14.0 |
| Wavelength | m | 0.0214 |
| Earth station EIRP | dBW | 79.0 |
| Satellite G/T | dB/K | 2.0 |
| Free space loss | dB | 206.9 |
| Rain region | | D2 |
| Availability | percent | 99.95 |
| Rain attenuation | dB | 5.9 |
| Antenna pointing error | deg | 0.02 |
| Antenna pointing loss | dB | 0.2 |
| Boltzmann's constant | dBW/K Hz | -228.6 |
| C/No (uplink) | dBHz | 96.6 |
| Noise bandwidth | dBHz | 73.5 |
| C/N (uplink) | dB | 23.1 |
| Power flux density | dBW/m$^2$ | -89.6 |

# Example link budget (continued)

***Downlink***

***Earth station receive terminal***

| | | |
|---|---|---|
| City | | Los Angeles |
| Longitude | deg | 118.1 |
| Latitude | deg | 34.0 |
| Earth central angle | deg | 39.4 |
| Elevation angle | deg | 44.4 |
| Slant range | km | 37453 |
| Antenna diameter | m | 5.0 |
| Antenna half power beamwidth | deg | 0.35 |
| Antenna efficiency | | 0.60 |
| Antenna receive gain | dB | 53.7 |
| Clear sky antenna noise temperature | K | 25 |
| Receiver equivalent temperature | K | 125 |
| System temperature | K | 150 |
| | dBK | 21.8 |
| G/T (clear sky) | dB/K | 32.0 |

***Link calculation***

| | | |
|---|---|---|
| Frequency | GHz | 12.0 |
| Wavelength | m | 0.025 |
| Satellite EIRP | dBW | 49.2 |
| Earth station G/T (clear sky) | dB/K | 32.0 |
| Free space loss | dB | 205.5 |
| Rain region | | F |
| Availability | percent | 99.95 |
| Rain attenuation | dB | 1.9 |
| Degradation in G/T | dB | 2.2 |
| Gaseous atmospheric loss | dB | 0.1 |
| Antenna pointing error | deg | 0.05 |
| Antenna pointing loss | dB | 0.2 |
| Boltzmann's constant | dBW/K Hz | -228.6 |
| C/No (downlink) | dBHz | 99.9 |
| Noise bandwidth | dBHz | 73.5 |
| C/N (downlink) | dB | 26.3 |

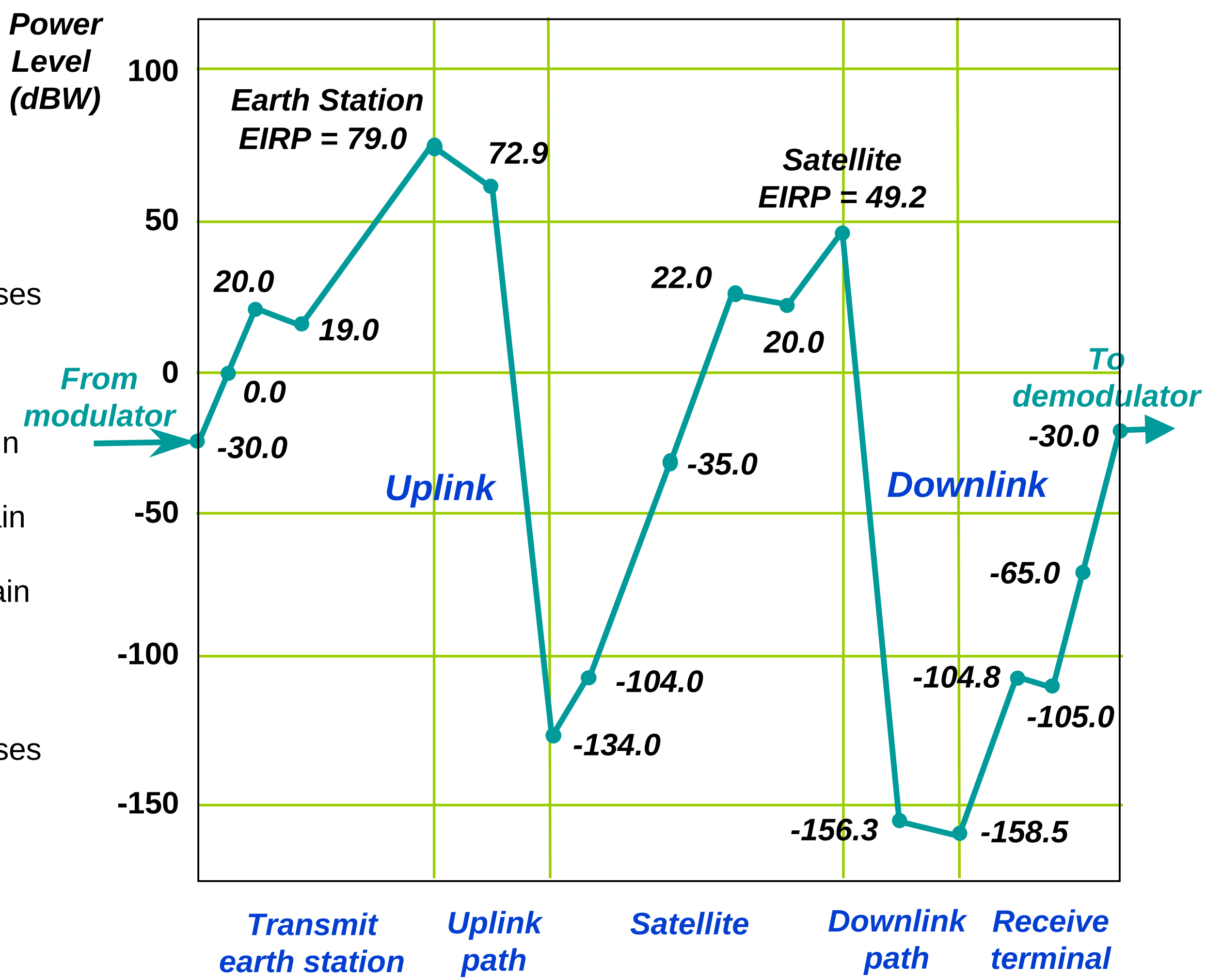
# Example link budget (continued)

***Combined uplink and downlink***

| | | |
|---|---|---|
| C/N (uplink) | dB | 23.1 |
| C/N (downlink) | dB | 26.3 |
| C/I (adjacent satellite) | dB | 20.0 |
| C/I (cross polarization) | dB | 24.0 |
| C/N (net) | dB | 16.7 |
| Noise bandwidrh | dBHz | 73.5 |
| C/No (net) | dBHz | 90.3 |
| Information bit rate | dBHz | 73.5 |
| Eb/No (available) | dB | 16.7 |
| | | |
| Eb/No (required) | dB | 5.0 |
| C/No (required) | dBHz | 78.5 |
| Margin | dB | 11.7 |

# Power levels in satellite link

| | |
|---|---|
| -30.0 dBW | Output of modulator and upconverter |
| **Uplink path** | |
| 30.0 dB | Driver gain |
| 20.0 dB | Earth station HPA gain |
| 1.0 dB | Line loss |
| 60.0 dB | Earth station antenna gain |
| 6.1 dB | Rain attenuation + other losses |
| 206.9 dB | Free space loss |
| **Satellite** | |
| 30.0 dB | Satellite receive antenna gain |
| 69.0 dB | Receiver amplifier gain |
| 57.0 dB | Satellite TWTA saturated gain |
| 2.0 dB | Output losses |
| 29.2 dB | Satellite transmit antenna gain |
| **Downlink path** | |
| 205.5 dB | Free space loss |
| 2.2 dB | Rain attenuation + other losses |
| 53.7 dB | Earth station antenna gain |
| 0.2 dB | Line loss |
| 40.0 dB | LNA gain |
| 35.0 dB | Downconverter and IF amplifier gain |
| -30.0 dBW | Input to demodulator |



# RF link (summary)

## Antenna half power beamwidth

$$\text{HPBW} = \alpha = k\frac{\lambda}{D} = k\frac{c}{f\,D}$$

## Antenna gain

$$G = \eta^* \frac{4\pi}{\Omega_A} = \eta' \frac{4\pi}{\Omega} = \eta \frac{4\pi}{\lambda^2} A = \eta\left(\frac{\pi D}{\lambda}\right)^2$$

## Free space loss

$$L_s = \left(\frac{4\pi d}{\lambda}\right)^2 = \left(\frac{4\pi d\, f}{c}\right)^2$$

## Carrier to noise density ratio

$$\frac{C}{N_0} = R_b\frac{E_b}{N_0} = \frac{G_t\,G_r}{L_s\,L}\,\frac{P_{in}}{k_B\,T} = \frac{\text{EIRP}\,(G_r/T)}{L_s\,L\,k_B}$$

$\alpha$ = half power beamwidth

$\lambda$ = wavelength

$f$ = frequency

$c$ = speed of light

$D$ = antenna diameter

$k$ = antenna taper factor

$\eta^*$, $\eta'$, $\eta$ = antenna efficiency factors

$\Omega_A$ = antenna beam solid angle

$d$ = slant range

$S$ = footprint area

$A$ = antenna area

$C$ = carrier power

$N_0$ = noise density

$R_b$ = information bit rate

$E_b$ = energy per information bit

EIRP = equivalent isotropic radiated power

$G_t$ = transmit antenna gain

$G_r$ = receive antenna gain

$P_{in}$ = input power

$L_s$ = free space loss

$L$ = net attenuative loss

$T$ = system noise temperature

$k_B$ = Boltzmann's constant

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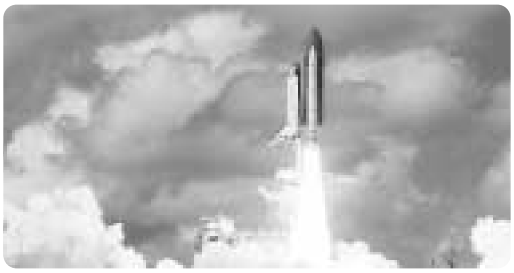

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