Professional Development Short Course On:

Satellite Communications Design & Engineering

Instructor:

Christopher DeBoy

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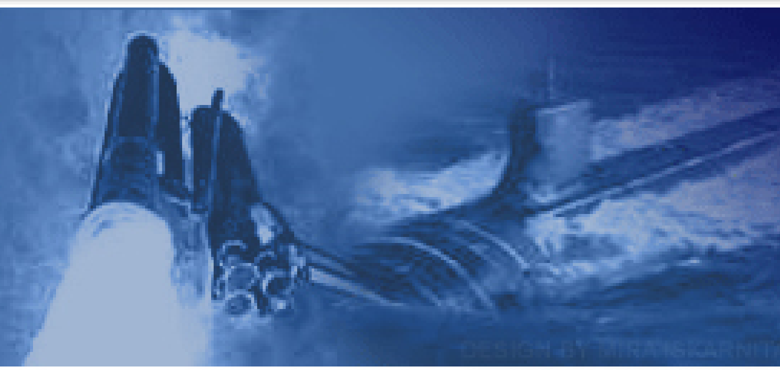

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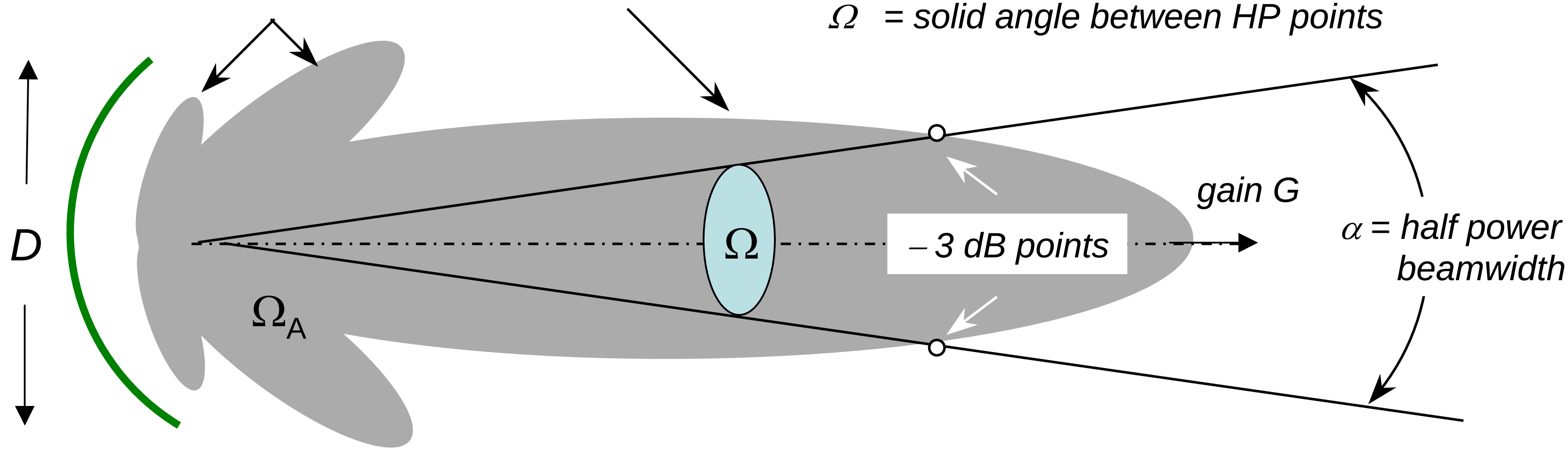
Outline

The RF Link

(Excerpt)

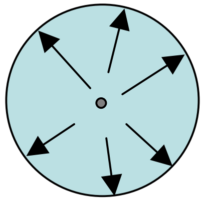
Antenna pattern, beamwidth, and gain



Beamwidth shows size of beam.

$$\text{HPBW} = \alpha = k\,\frac{\lambda}{D} = 70^\circ\,\frac{\lambda}{D}$$ 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 η^*, η', η = measures of antenna efficiency

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

Example: Earth terminal antenna

Prime Focus Feed; 5 meter reflector; Tx and Rx
C-Band gain 46 dB; Beamwidth = 1°
Ku-Band gain 54 dB; Beamwidth = 0.4°

Ku band downlink frequency
f = 12 GHz

$$\lambda = \frac{c}{f} = \frac{3\times 10^{8}\ \text{m/s}}{12\times 10^{9}\ \text{Hz}} = 0.025\ \text{m}$$

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

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

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

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 η^* is the antenna power loss efficiency, $P = \eta^* P_{in}$ is the transmitted power, S is the total coverage area at distance d, Ω_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,

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

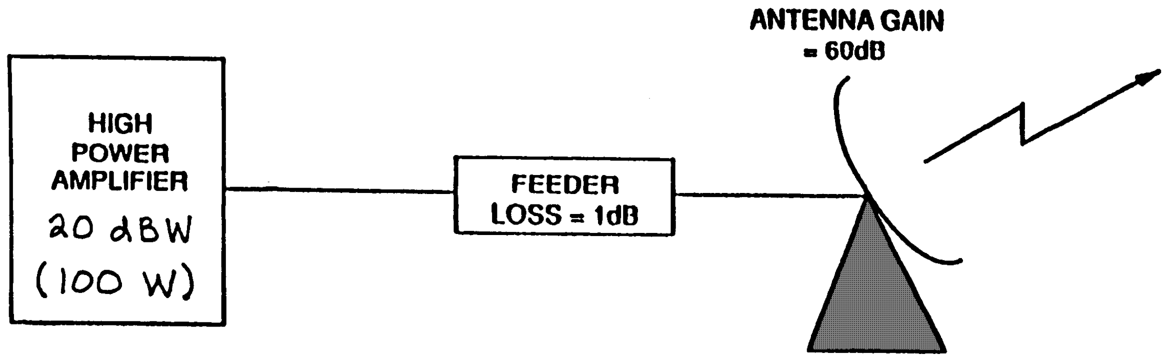
The EIRP is the product of the antenna transmit gain and the power applied to the *input* terminals of the antenna. The antenna efficiency η^* is absorbed in the definition of gain.

Example 1

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

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

Example 2



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

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

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

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."

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

where

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

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

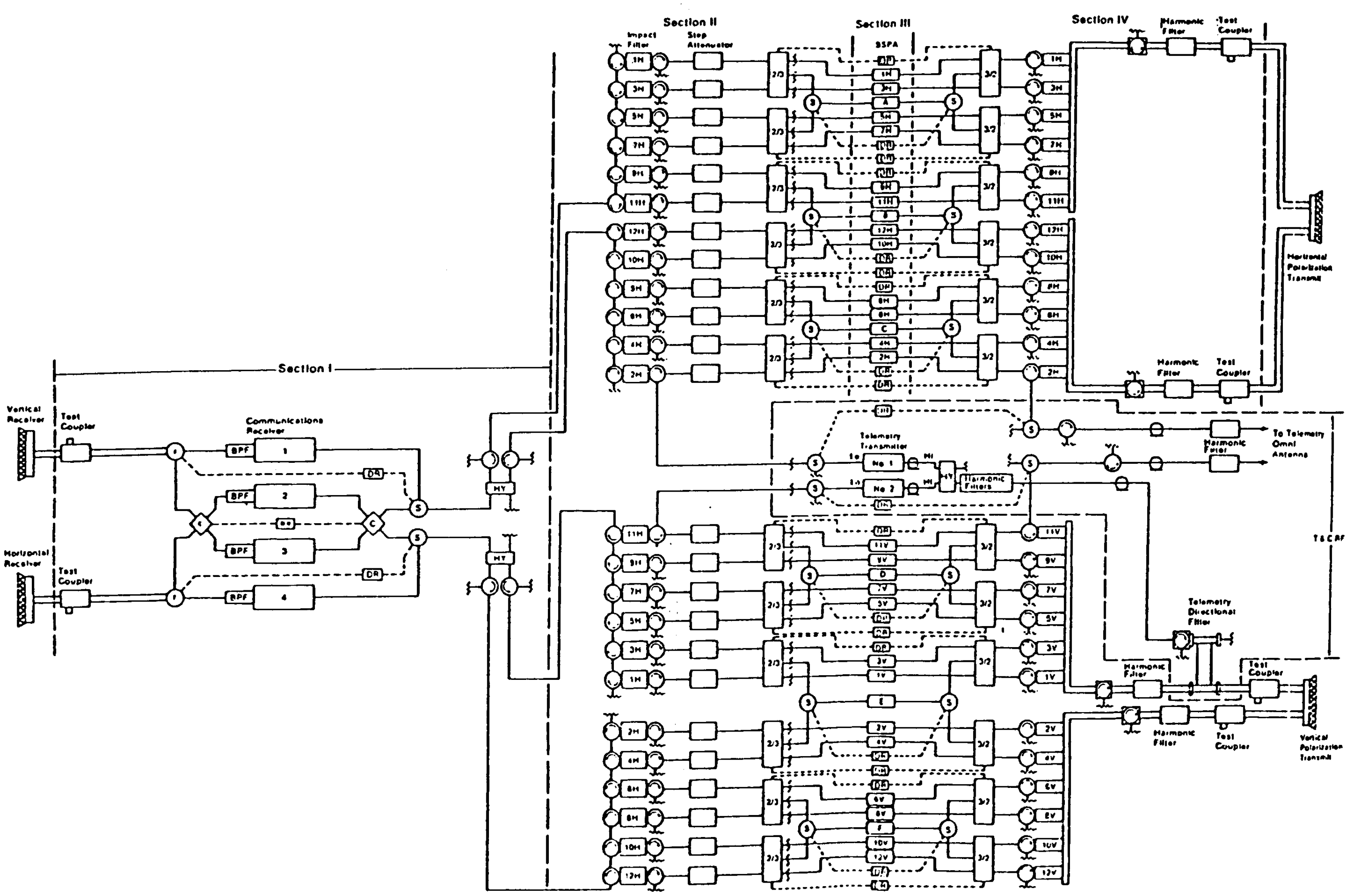
The figure of merit is independent of the point where it is calculated. However, the gain and system temperature must be specified at the same point.

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

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

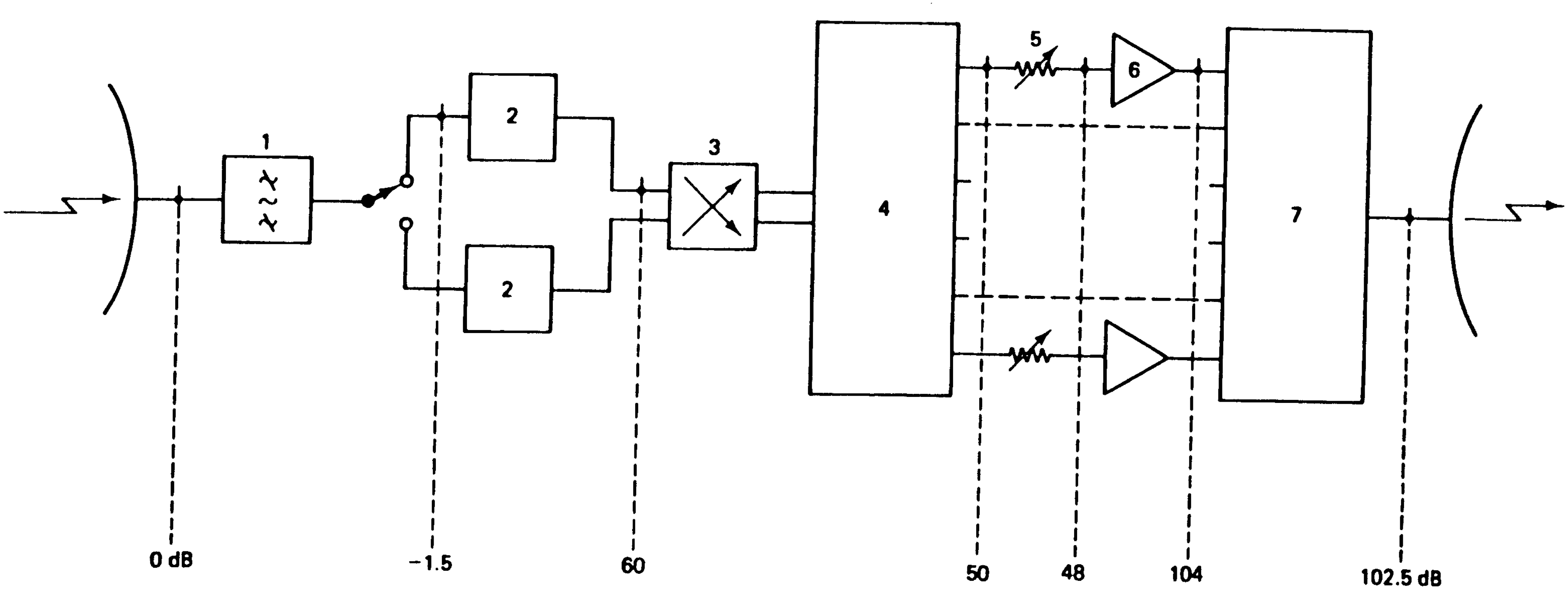
$$[\, G / T \,] = [\, G \,] - [\, T \,] = 53.7 \text{ dB} - 21.7 \text{ dBK} = 32.0 \text{ dB/K}$$

Satellite communications payload architecture



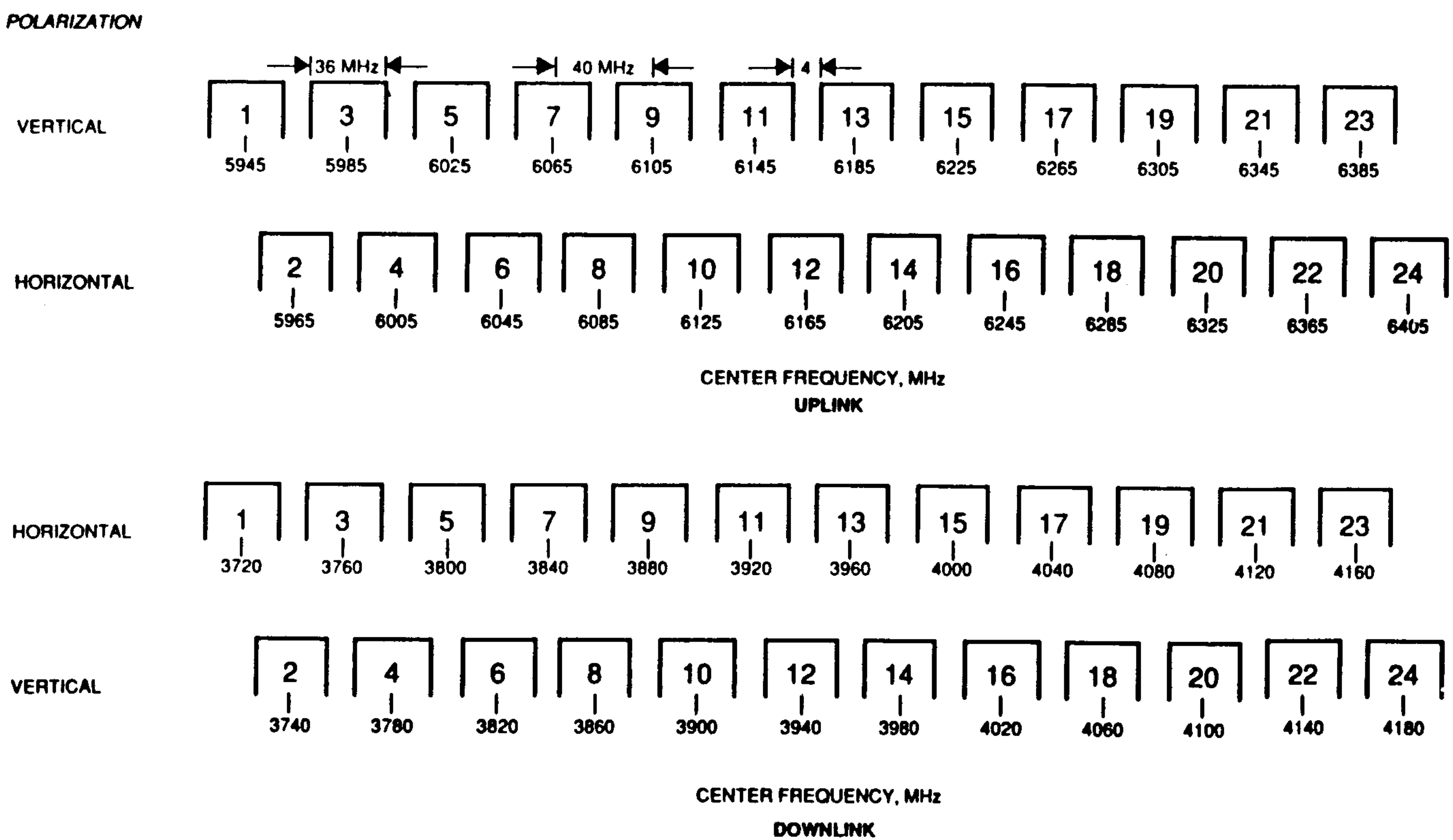
10

Transponder



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

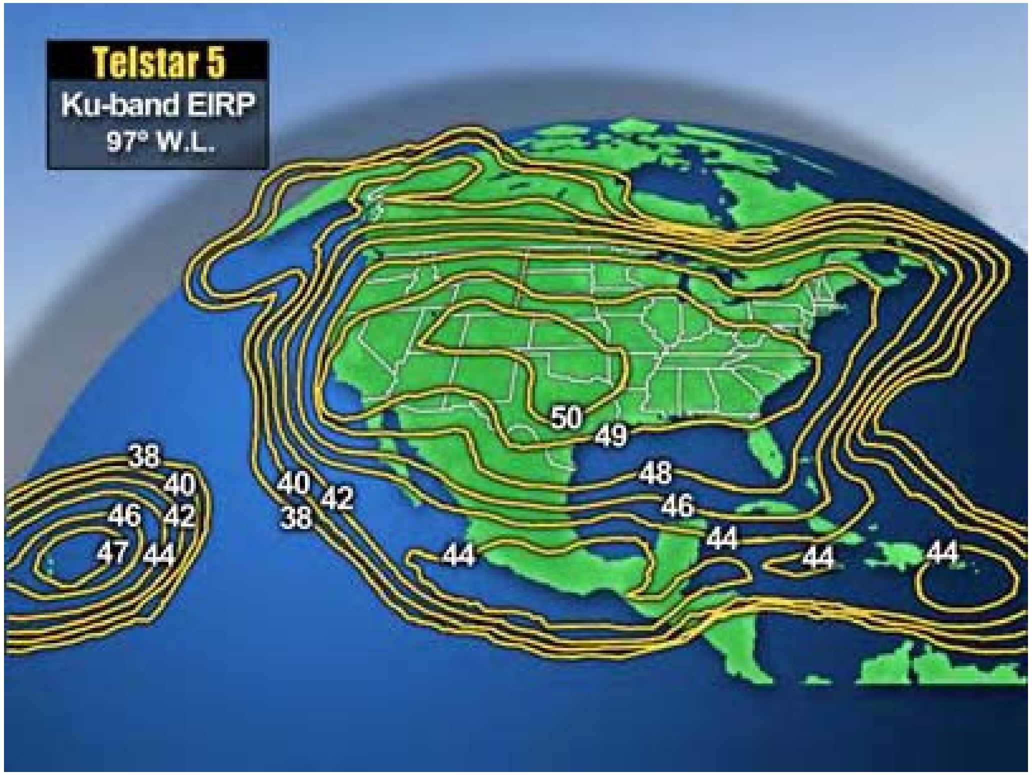
Frequency Band
4/6 GHz and 12/14 GHz

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

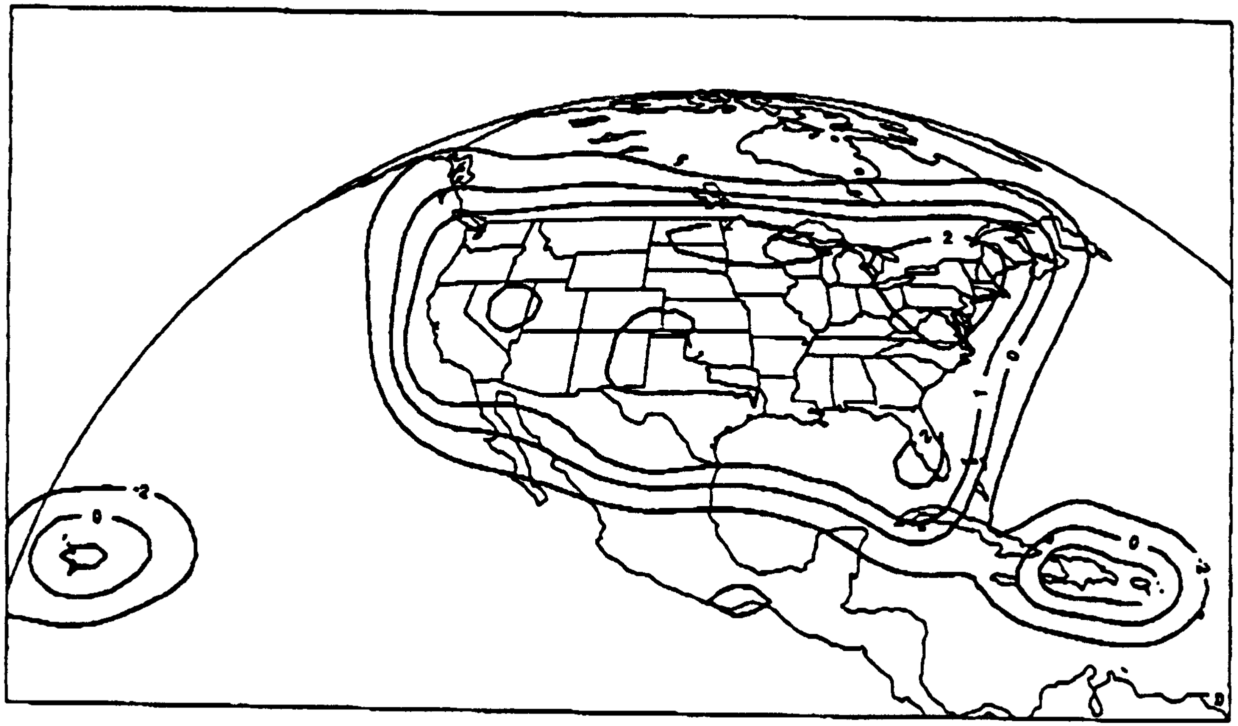
Satellite EIRP footprint



P = 100 W [P] = 20 dBW [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

θ = 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

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

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.

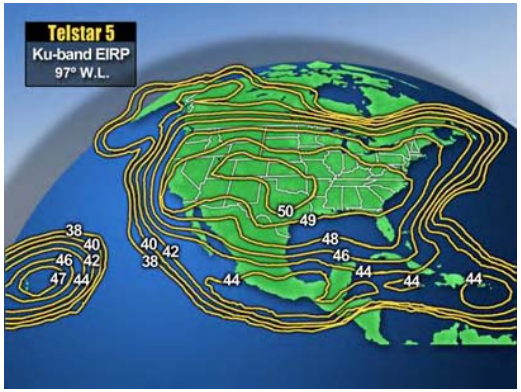
Solution: The satellite EIRP in Los Angeles is 49.2 dBW. At 12 GHz, the antenna gain is 53.7 dB and the free space loss is 205.5 dB. Therefore, the received carrier power is

$$[C]=[\mathrm{EIRP}]+[G_r]-[L_s]-[L_r]-[L_a]-[L_p]$$

$$=49.2\ \mathrm{dBW}+53.7\ \mathrm{dB}-205.5\ \mathrm{dB}$$

$$-1.9\ \mathrm{dB}-0.1\ \mathrm{dB}-0.2\ \mathrm{dB}$$

$$=-104.8\ \mathrm{dBW}$$



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

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

Noise power

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

Carrier to noise ratio

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

Carrier to noise density ratio

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

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 (dBW/m²) 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

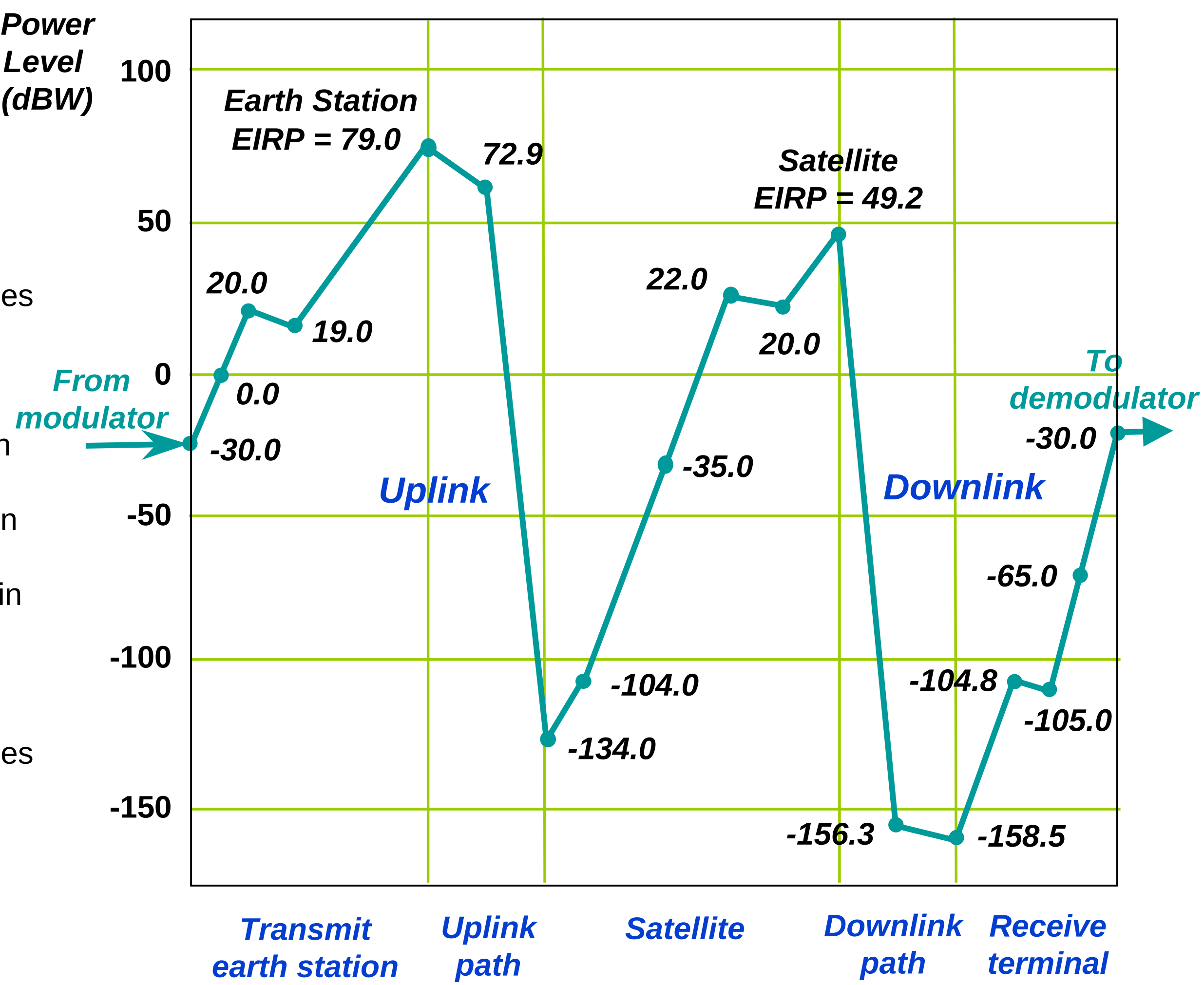
Example link budget (continued)

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

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

α = half power beamwidth

λ = wavelength

f = frequency

c = speed of light

D = antenna diameter

k = antenna taper factor

η^*, η', η = antenna efficiency factors

Ω_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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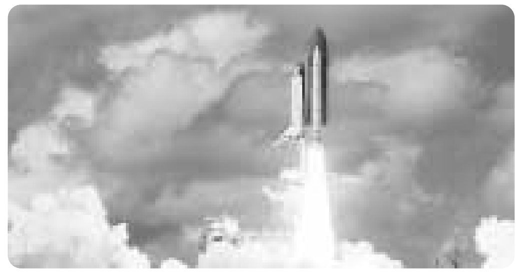

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