CS 294-7: Mobile Satellite Systems

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Mobile Satellite Systems

- Like cellular systems, except that the base stations (i.e., satellites) move as will as mobile devices
- Satellite coverage attractive for areas of world not well served by existing terrestial infrastructure: ocean areas, developing countries

Mobile Satellite Systems

- **Interesting aspects of the satellite link:**
  - 270 ms propagation delay (geosync)
  - Transmission cost independent of distance
  - Very high bit rates are possible; can avoid bandwidth limitations of terrestrial links
  - An inherently broadcast medium
  - Dynamic assignment of channels between geographically dispersed users
  - A transmitting station can receive its own transmission; can be exploited for transmission control

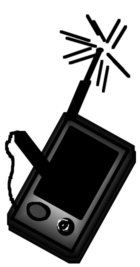
Mobile Satellite Systems

- **Assigned Frequencies**
  - P Band: 0.225-0.39 GHz
  - J Band: 0.35-0.53 GHz
  - L Band: 0.39-1.55 GHz
  - S Band: 1.55-5.2 GHz
  - C Band: 3.9-6.2 GHz
  - X Band: 5.2-10.9 GHz
  - K Band: 10.9-36.0 GHz
  - Ku Band: 15.35-17.25 GHz
  - Q Band: 36-46 GHz
  - V Band: 46-56 GHz
  - W Band: 56-100 GHz

Earlier satellites, interference with terrestrial microwave links (4/6 GHz)

Newer generation satellite systems (14/16 GHz)

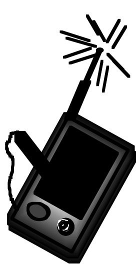
Also interest in 20/30 GHz systems (Ka Band, NASA ACTS)



- **Antenna gain proportional to f^2, free space loss to $1/f^2$**
- **Counterbalanced by noise and absorption issues**

Equivalent Isotropic Radiated Power (EIRP)

- **Maximum power flux density at distance r from a transmitting antenna of gain G:**
  - $\Psi_M = (G\ P_s) / (4\ \pi\ r^2)$
  - **An isotropic (omnidirectional) radiator would generate this flux density**
- **EIRP is defined as $G\ P_s$**
  - **When expressed as dBW, Ps in W, G in dB:**
    EIRP = P_s + G
  - **e.g., transmit power of 6 W and antenna gain of 48.2 dB:**
    EIRP = 10 log 6 + 48.2 = 56 dBW

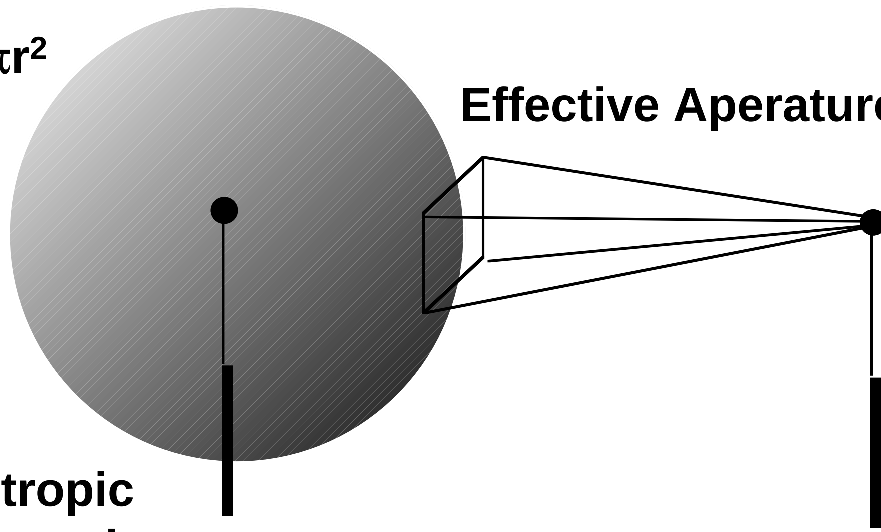


Free Space Loss: $P_R = EIRP + G_R - 10 \log (4\ \pi\ r / \lambda)^2$ (dBW)

Receiver Power Equation

$\Psi_m = EIRP/4\pi r^2$

Effective Aperature of Receiver Antenna



surface area
of the sphere
$= 4\,\pi\,r^2$

$P_R = \Psi_m\,A_{eff}$

A_{eff} is proportionality constant

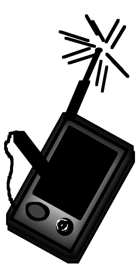
Isotropic
Transmitter

Receiver

Gain measures directionality of receiver antenna

$$G = \frac{\text{Max Flux Den}}{\text{Isotropic Flux Den}} = \frac{\Psi_m}{\Psi_i}$$

$A_{eff} = G\,\lambda^2 / 4\,\pi$ (antenna efficiency x aperature area)

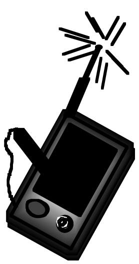


$$P_R = \frac{EIRP\;\;G_R\;\;\lambda^2}{4\,\pi\,r^2\;\;\;4\,\pi}$$: $EIRP + G_R - 10\log(4\,\pi\,r\,/\,\lambda)^2$ in dB

"Free Space Loss"

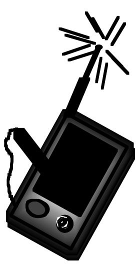
Free Space Loss

- **$FSL = 10 \log (4 \pi r / \lambda)^2$**
  - **in dBW , FSL = 32.4 + 20 log r + 20 log f**
  - **e.g., ES to satellite is 42,000 km, f is 6 GHz, what is FSL?**
    - » **FSL = 32.4 + 20 log 42000 + 20 log 6000 = 200.4 dB**
    - » **Very large loss!!**
  - **e.g., EIRP = 56 dBW, receive antenna gain 50 dB**
    - » **P_R = 56 + 50 - 200.4 = -94.4 dBW = 355 pW**
- **Other sources of losses**
  - **Feeder losses**
  - **Antenna misalignment losses**
  - **Fixed atmospheric and ionospheric losses**
  - **Effects of rain**
- **P_R = EIRP + G_R - Losses, in dBW**



Noise Sources

- **System Noise**
  - Received power is very small, in picowatts
  - Thermal noise from random motion of electrons
  - Antenna noise: antenna losses + sky noise (background microwave radiation)
  - Amplifier noise temperature: energy absorption manifests itself as heat, thus generating thermal noise
- **Carrier-to-Noise Ratio**
  - $C/N = P_R - P_N$ in dB
  - $P_N = k\,T_N\,B_N$
  - $C/N = EIRP + G_R - LOSSES - k - T_S - B_N$
    where k is Boltzman's constant, T_S is system noise temperature, T_N is equivalent noise temperature, B_N is the equivalent noise bandwidth
  - Carrier to noise power density (noise power per unit b/w): $C/N_0 = EIRP + G/T - Losses - k$



Noise

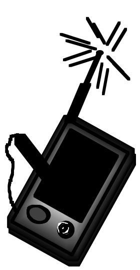
Shannon's Law: $B = B_N \log_2 (P_R / P_N + 1)$
Where B = information-carrying capacity of the link (bits/unit bandwidth)
B_N = usable bandwidth (hertz)
P_R/P_N must not get too small!

Noise power usually quoted in terms of noise temperature: $P_N = k\, T_N\, B_N$

The noise temperature of a noise source is that temperature that produces the same noise power over the same frequency range: **$T_N = P_N / k\, B_N$**

Noise density (noise per hertz of b/w): $N_0 = P_N / B_N = k\, T_N$

Carrier-to-Noise: $C/N_0 = P_R / N_0 = P_R / k\, T_N$: EIRP + G/T - k - Losses in dB



Receiver antenna figure of merit: increases with antenna diameter and frequency;

More powerful xmit implies cheaper receiver

Sun, Moon, Earth, Galactic Noise, Cosmic Noise, Sky Noise, Atmospheric Noise, Man-made Noise

Carrier-to-Noise Ratio Example Calculation

- **Example:**
  - 12 GHz frequency,
    free space loss = 206 dB,
    antenna pointing loss = 1 dB,
    atmospheric absorption = 2 dB
  - Receiver G/T = 19.5 dB/K,
    receiver feeder loss = 1 dB
  - EIRP = 48 dBW
- **Calculation:**
  - $C/N_0 = -206 - 1 - 2 + 19.5 - 1 + 48 + 228.6 = 86.1$
    (Note that Boltzmann's constant $k = 1.38 \times 10^{-23}$ J/K = -228.6 dB)
  - Bottom-line: while the received signal is very small, the background noise sources are even smaller (but many other effects increase the noise temperature, like rain absorption)

Simplified Link Equation

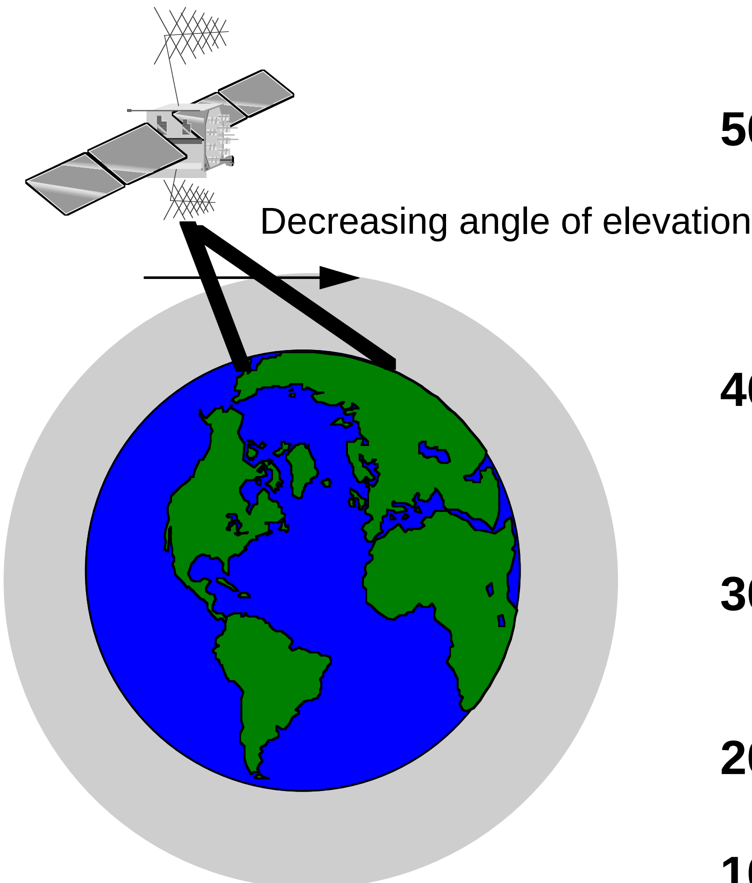
- $10 \log (C/N_0) = P_S + G_S - FS\ L + G_R - T_R - k - L$ dB where
  - C/N_0: ratio of signal pwr to noise pwr after being received (Hz)
  - P_S: RF pwr delivered to transmitting antenna (dBW)
  - G_S: Gain of the transmitting antenna relative to isotropic rad (dBi)
  - FSL: Free space loss (dB)
  - G_R: Gain of the receiving antenna (dBi)
  - T_R: Composite noise temperature of the receiver (dBK)
  - k: Boltzmann's constant (-288.6 dBW/K-Hz)
  - L: Composite of propagation loss (dB)
- $G = 10 \log (\eta\ \pi^2\ D^2/\lambda^2)$ dBi
  - η: antenna efficiency, D: diameter
- $FSL = 10 \log [(4\ \pi\ r)^2/\lambda^2]$ dB
  - r is distance

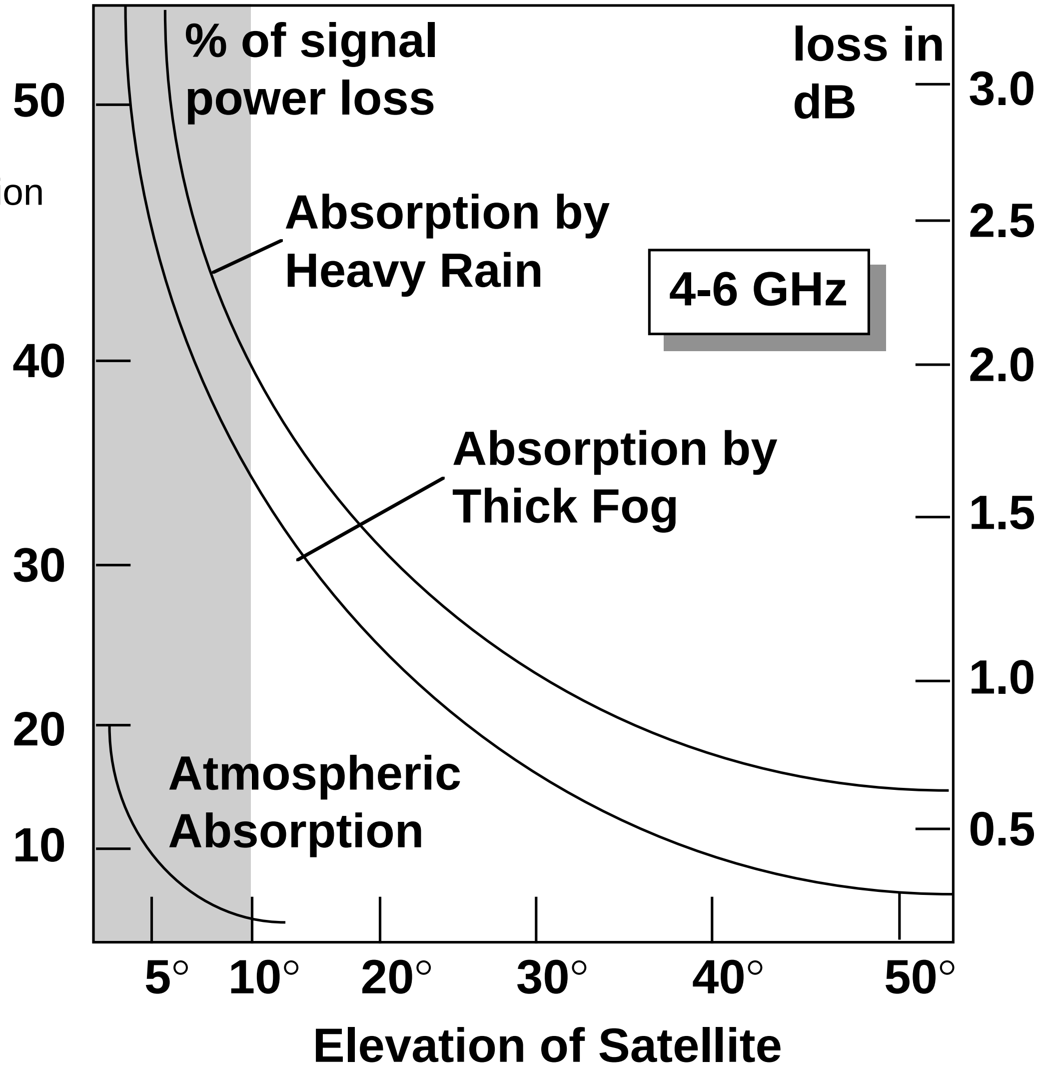
Path loss and antenna gain increase with square of radio frequency

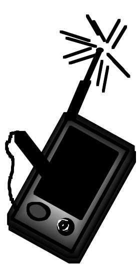
Frequency vs. Losses vs. BER

- Higher transmission frequency has the advantage of requiring a smaller receiver antenna
- BUT suffers from higher attenuation losses through atmosphere
- To achieve the same C/N_0 performance, which is related to BER, actually needs a LARGER antenna than same transmission power at a lower frequency
- But still frequency allocation advantages for high frequencies
- Solution is to use higher transmitter power at the satellite and earth station for the higher frequency transmissions

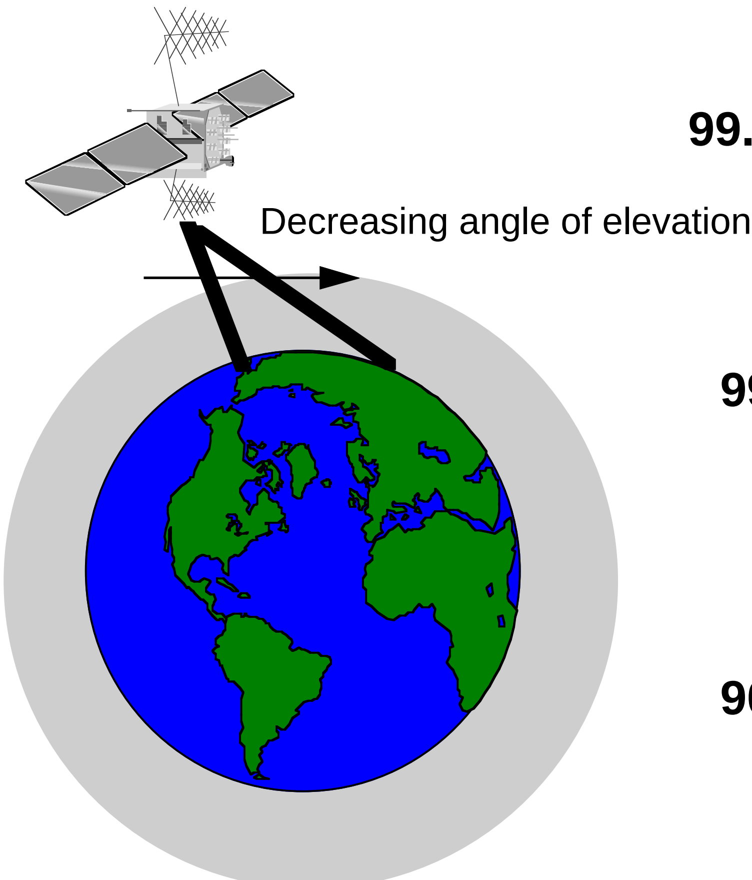
Atmospheric Attenuation

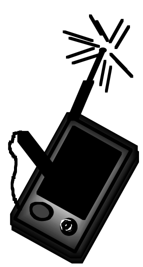


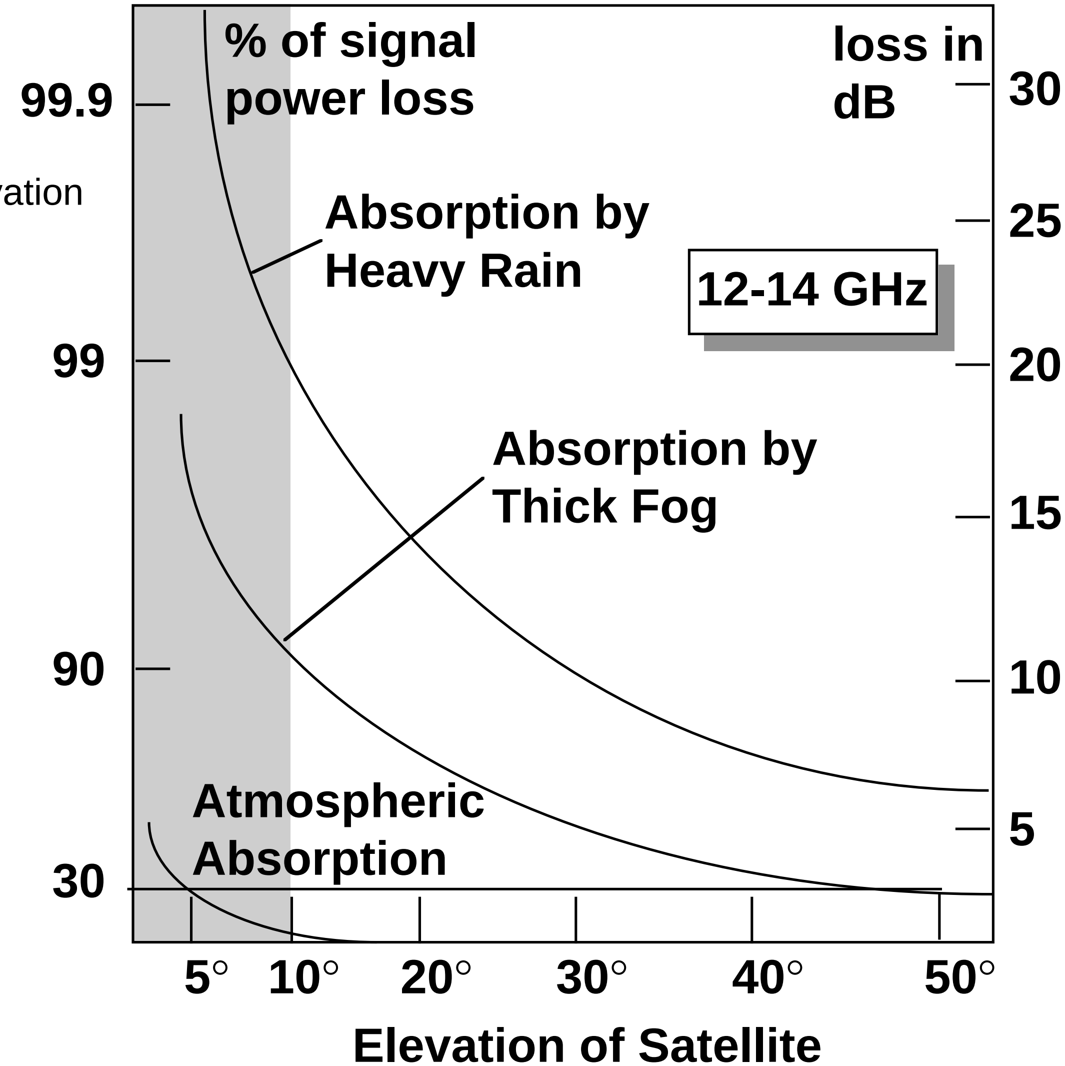




Atmospheric Attenuation







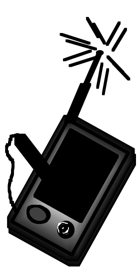
Atmospheric Absorption

- Contributing Factors:
  - Molecular oxygen
  - Uncondensed water vapor
  - Rain
  - Fog and clouds
  - Snow and hail

Constant

Depend on weather

- Effects are frequency dependent
  - Molecular oxygen absorption peaks at 60 GHz
  - Water molecules peak at 21 GHz
- Decreasing elevation angle will also increase absorption loss

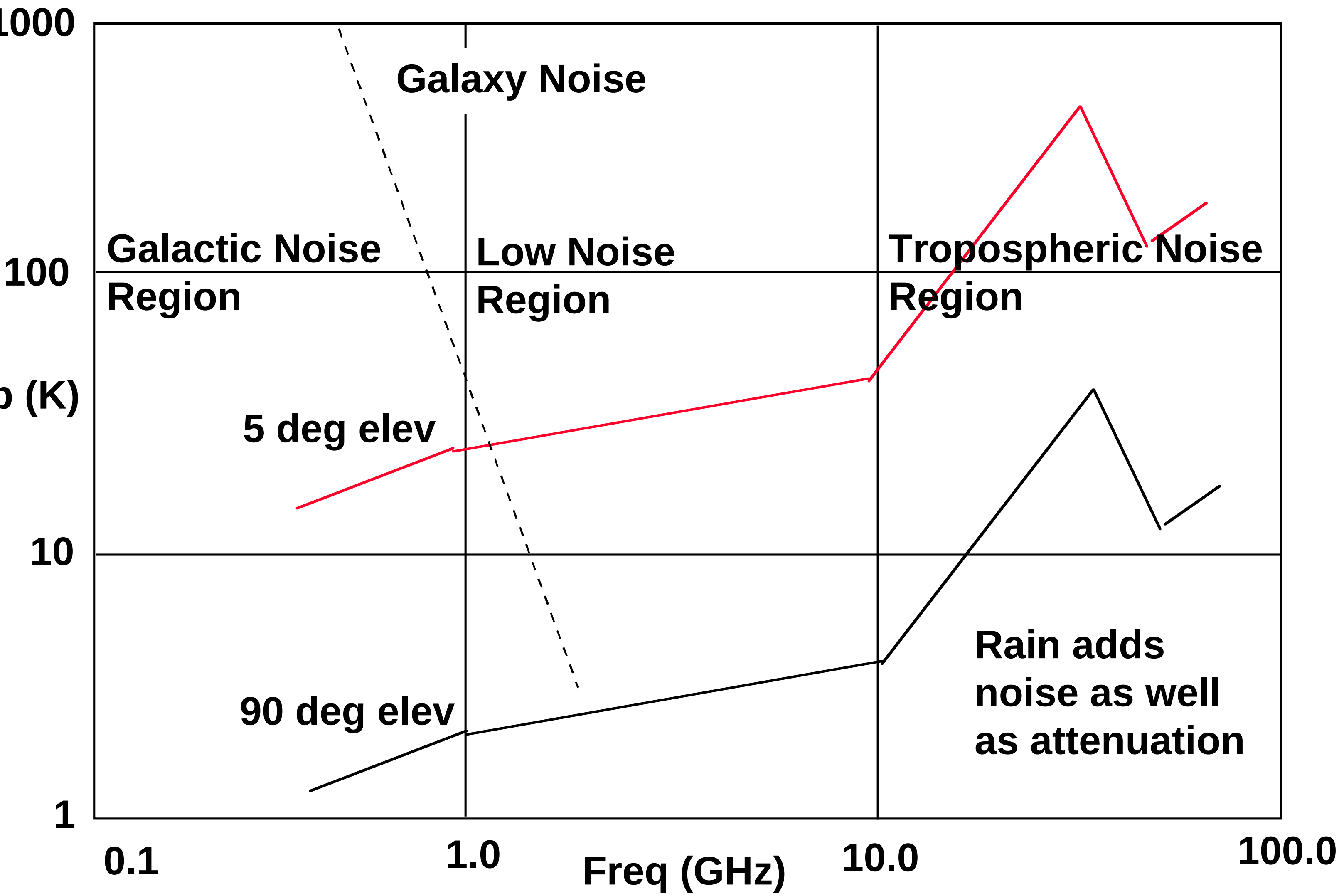


Atmospheric Absorption

Location	Rain Attenuation, dB 1%	0.5%	0.1%	Atmos Absorp dB, Summer	Sat Ant Pointing Loss, dB 1/4 Canada Coverage	1/2 Canada Coverage
Ottawa	0.3	0.5	1.9	0.2	0.6	0.2
Toronto	0.2	0.6	1.8	0.2	0.3	0.4

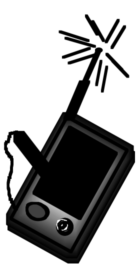
1% of the time, rain attenuation exceeds 0.3 dB
(99% of the time, it is less than or equal to 0.3 dB)
0.5% of the time, it exceeds 0.5 dB
0.1% of the time, it exceeds 1.9 dB

Antenna Temperature



Rain and Signal Losses

- **Rain Effect**
  - **Rainfall introduces attenuation by absorption and scattering of signal energy**
  - **Absorptive attenuation introduces noise**
    - » **A dB rain attenuation yields power loss ratio of $10^{A/10}$**
    - » **Effective noise temperature of rain $T_{Rain} = T_A (1 - 1/A)$**
    - » **T_A is a measured quantity between 270 and 290 K**
  - **Suppose "clear sky" C/N is 20 dB, effective noise temperature is 400 K, apparent absorber temperature is 280 K, rain attenuation exceeds 1.9 dB 0.1% of time, how does this effect C/N?**
    - » **1.9 dB = 1.55:1 power loss *(i.e., $10^{1.9/10} = 1.55$)***
    - » **$T_{rain} = 280(1-1/1.55) = 99.2$ K**
    - » **400 + 99.2 = 499.2 K**
      change in noise power is 499.2 - 400 = 0.96 dB
      (= 10 log (499.2/400))
    - » **C/N = 20 - 1.9 - 0.96 = 17.14 dB**

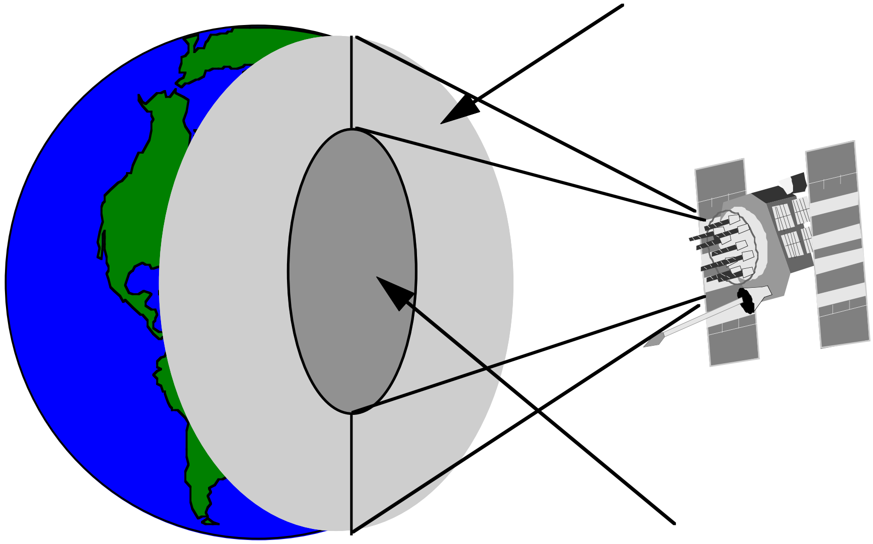


Transmission Losses

- **Up-Link (Geosync)**
  - Up-link f = 6.175 GHz, D = 36,000 km
  - Path loss is a function of frequency and distance minus transmitter and receiver antenna gain
  - Loss = 132.7 - 20 log dt - 20 log dr
    dt transmitter antenna: 30 m
    dr satellite receiver antenna: 1.5 m
  - Loss = 132.7 - 29.5 - 3.5 = 94.7 dB
    Transmitted pwr/received pwr = 2.95×10^9
- **Down-Link**
  - Down-link f = 3.95 GHz
  - Footprint of antenna affects its gain; wide area footprint yields a lower gain, narrow footprint a higher gain
  - Loss = 136.6 - 20 log dt - 20 log dr
    Loss = 136.6 - 3.5 - 29.5 = 103.6 dB

Downlink Footprint

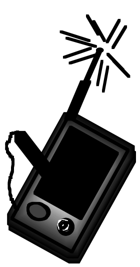
π x 3962² square miles (full earth coverage)



$$G = \frac{4\pi\ 24000^2}{\pi\ 3962^2} = 147 = 22\ \text{dB}$$

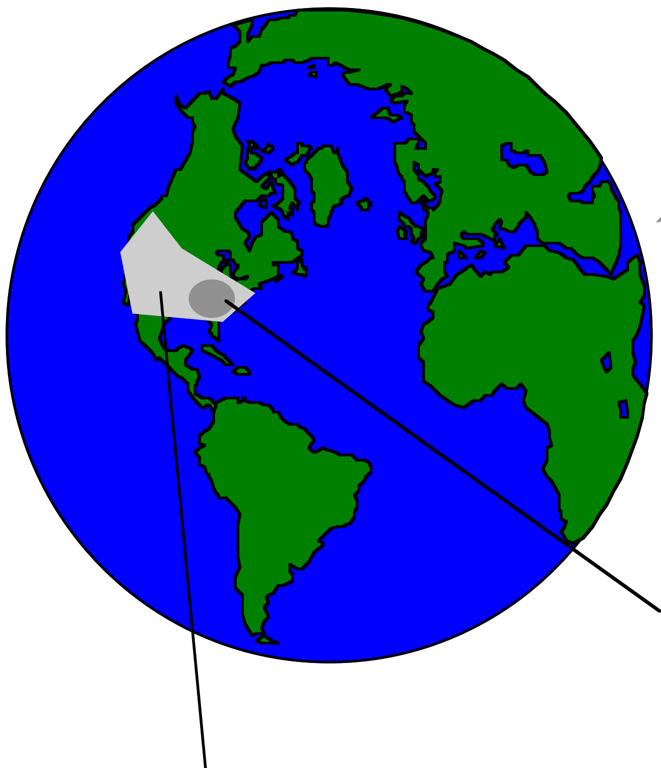
π x 1500² square miles (CONUS coverage)

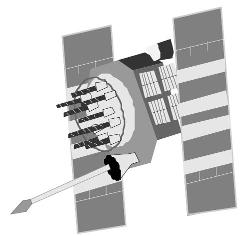
$$G = \frac{4\pi\ 24000^2}{\pi\ 1500^2} = 1024 = 30\ \text{dB}$$



Greater directionality implies antenna larger size or increased frequency
4 x antenna covering area 1/4 of size yields gain 16 x as great (12 dB)

Downlink Footprint





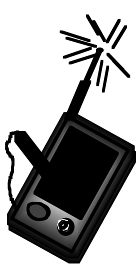
36 MHz transponder:
- One color TV channel OR
- 1200 voice channels OR
- 50 Mbps data rate

Antenna is beam formed to provide specific coverage areas

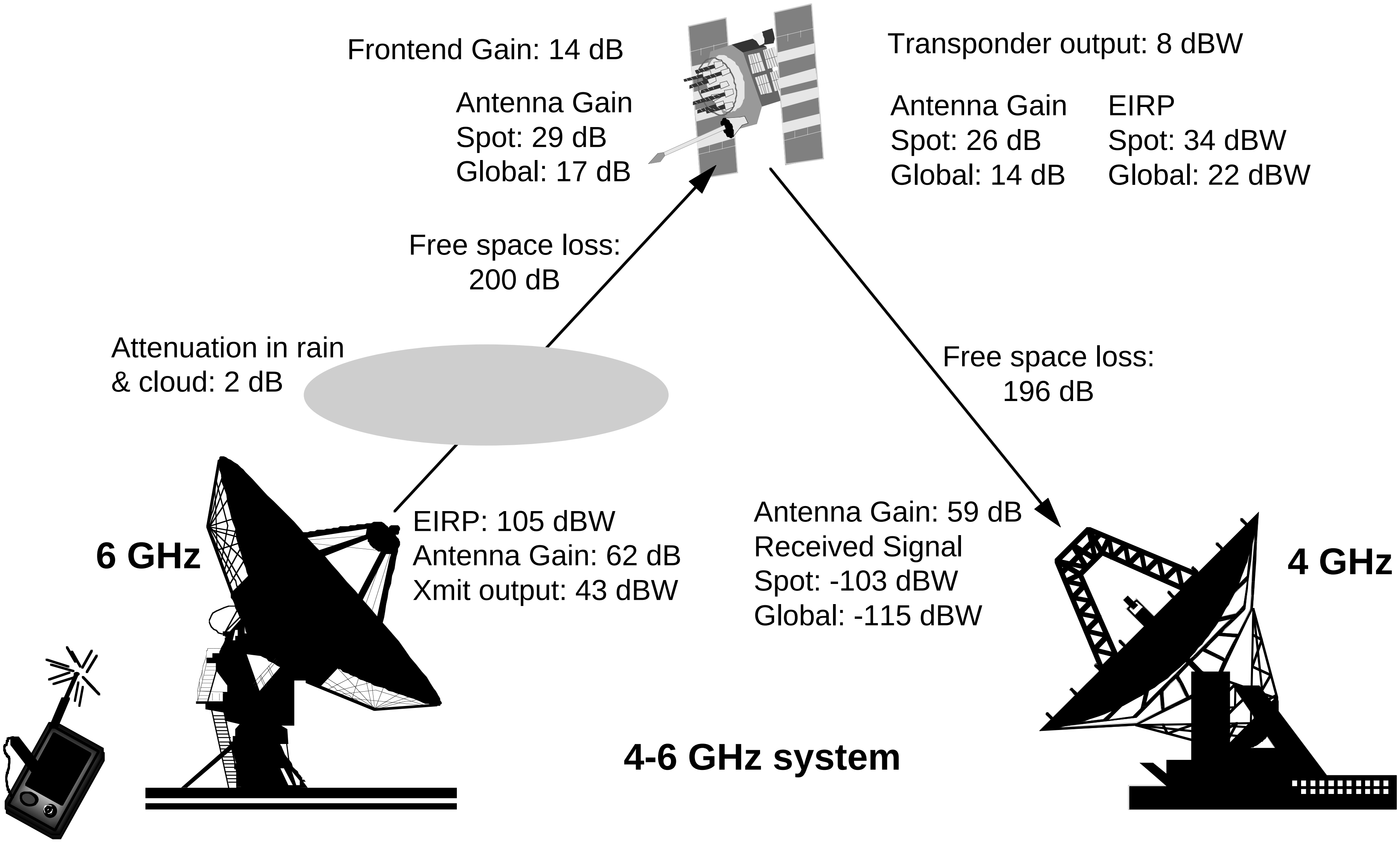
Spot beams: high power, narrow beam

Strong signal to support smaller antennas vs. worse weather

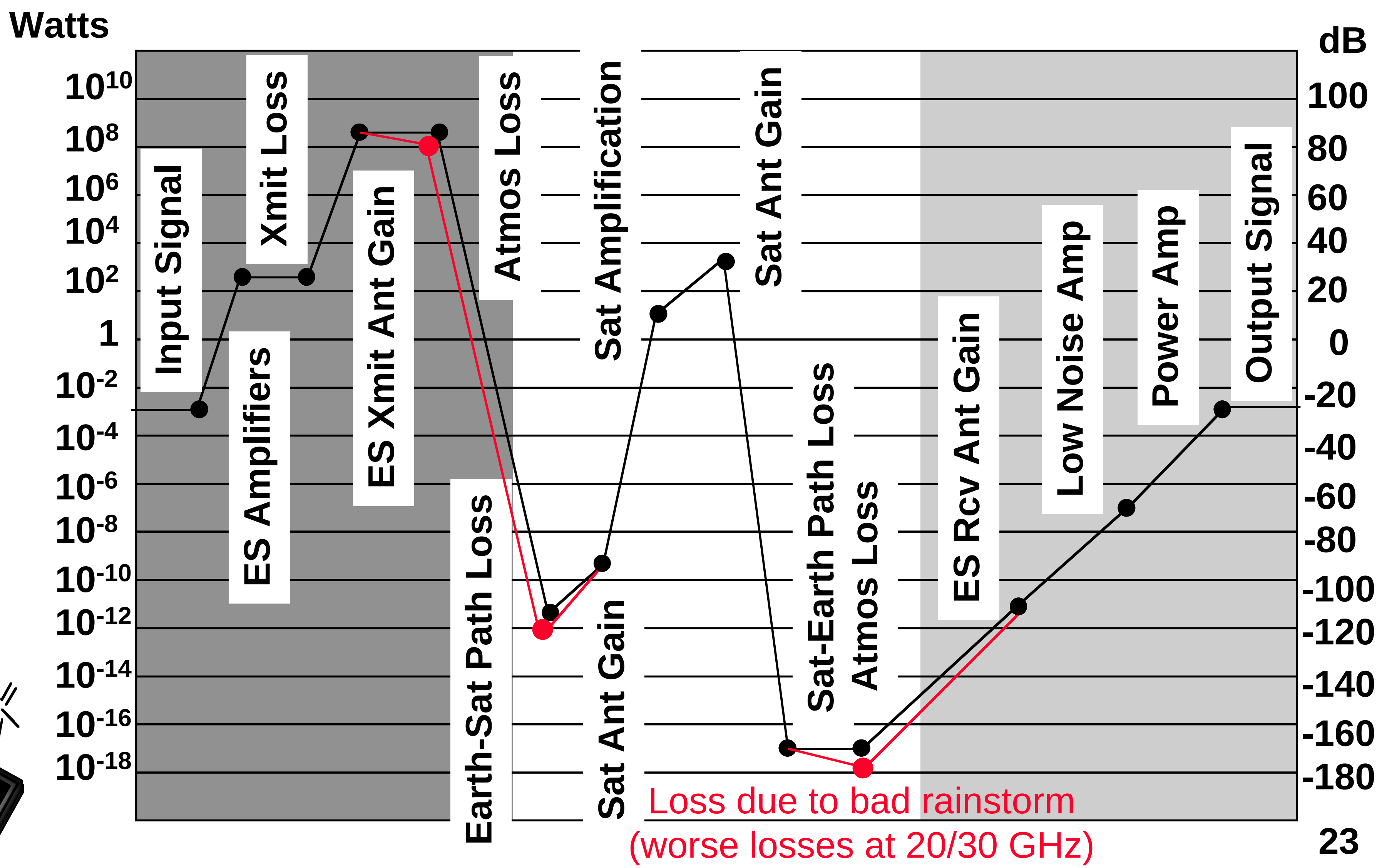
Weaker signal requires larger antennas

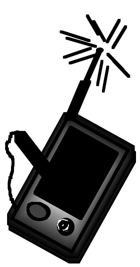


Typical Losses



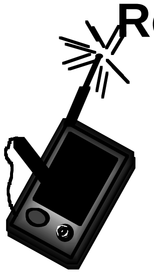
Typical Losses (4/6 GHz)





Satellite Link Summary: Up-Link

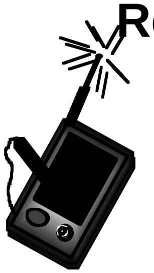
	4/6 GHz	12/14 GHz	20/30 GHz	12/14 GHz
Transmitter power, dBw	35	25	20	20
Transmitter system loss, dB	-1	-1	-1	-1
Transmitter antenna gain, dB	55	46	76	62
Atmospheric loss, dB	0	-0.5	-2	-0.5
Free space loss, dB	-200	-208	-214	-208
Receiver antenna gain, dB	20	46	53	60
Receiver system loss, dB	-1	-1	-1	-1
Received power, dBw	-92	-93.5	-69	-68.5
Noise temperature, °K	1000	1000	1000	1000
Received b/w, MHz	36	36	350	36
Noise, dBw	-128	-128	-118	-128
Received SNR, dB	36	34.5	49	59.5
Loss in bad storm, dB	2	10	25	10
Received SNR in bad storm, dB	34	24.5	24	49.5



DBS, receive-only ES
1.8 m, 9 m satellite antenna

Satellite Link Summary: Down-Link

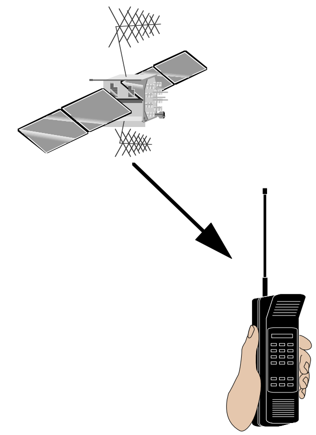
	4/6 GHz	12/14 GHz	20/30 GHz	12/14 GHz
Transmitter power, dBw	18	20	8	10
Transmitter system loss, dB	-1	-1	-1	-1
Transmitter antenna gain, dB	16	44	49	58
Atmospheric loss, dB	-197	-206	-210	-206
Free space loss, dB	0	-0.6	-2	-0.6
Receiver antenna gain, dB	51	44	72	44
Receiver system loss, dB	-1	-1	-1	-1
Received power, dBw	-114	-100.6	-85	-96.6
Noise temperature, °K	250	1000	250	1000
Received b/w, MHz	36	36	350	36
Noise, dBw	-131	-128	-121	-128
Received SNR, dB	17	27.4	36	31.4
Loss in bad storm, dB	2	10	25	10
Received SNR in bad storm, dB	15	17.4	11	21.4

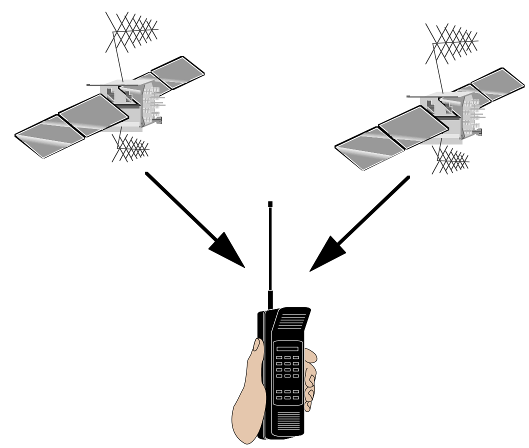


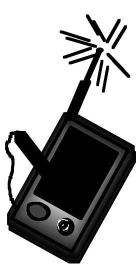
DBS, receive-only ES
1.8 m, 9 m satellite antenna

Satellite Path Diversity for Improved Service Availability

- **Two alternatives:**
  - Single path, "medium power" (16-17 dB link margin)
    - » Still mostly line of sight service
    - » Handoff will improve service availability but only if more satellites in view
  - Multiple path, "low power" (7-8 dB+ link margin)
    - » Substantial improvements in service availability
    - » Handoff further improves service availability
    - » Works with any orbit







DBS Systems

	High Power	Medium Power	Low Power
Band	Ku	Ku	C
Downlink freq alloc, GHz	12.2-12.7	11.7-12.2	3.7-4.2
Uplink freq alloc, GHz	17.3-17.8	14-14.5	5.925-6.425
Primary Use	DBS	Pt-to-Pt	Pt-to-Pt
Secondary Use	Pt-to-Pt	DBS	DBS
Terrestrial Interference	No	No	Yes
Satellite Spacing	9 deg	2 deg	2-3 deg
Determined by	ITU	FCC	FCC
Satellite Interference	No	Yes	Yes
Satellite EIRP, dBW	51-60	40-48	33-37

Ku band: less utilized; not used in land-based microwave systems, 60 cm dishes (vs. 3 m C-band dishes)

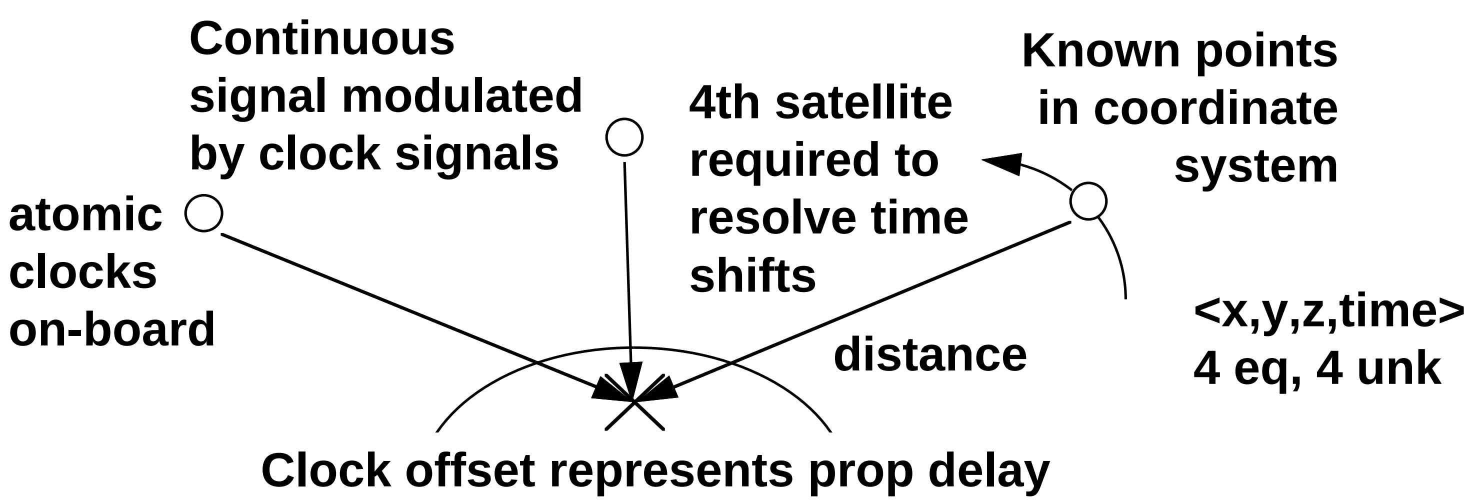
DBS Systems

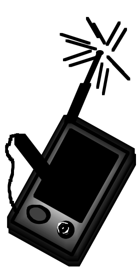
Parameter	High Power	Medium Power	Low Power
Downlink Band, GHz	12.2-12.7	11.7-12.2	3.7-4.2
Satellite Coverage	Full/Half	Full/Half	Full CONUS
Transponder pwr, W	100-260	15-45	5-10
Transponder EIRP, dBW	51-58	40-48	33-37
Polarization*	RHC/LHC	H/V	H/V
Typ Transponders per Sat	8-16	10-16	24
Transponder b/w, MHz	24	43-72	36
Home Antenna Diam, m	0.3-0.8	1-1.6	2.5-4.8
Receiver Noise Temp, K	100-200	100-200	35-80
Cost, US$	400-800	600-1200	2000-4000

* RHC: right hand circular, LHC: left hand circular,
H: horizontal, V: vertical

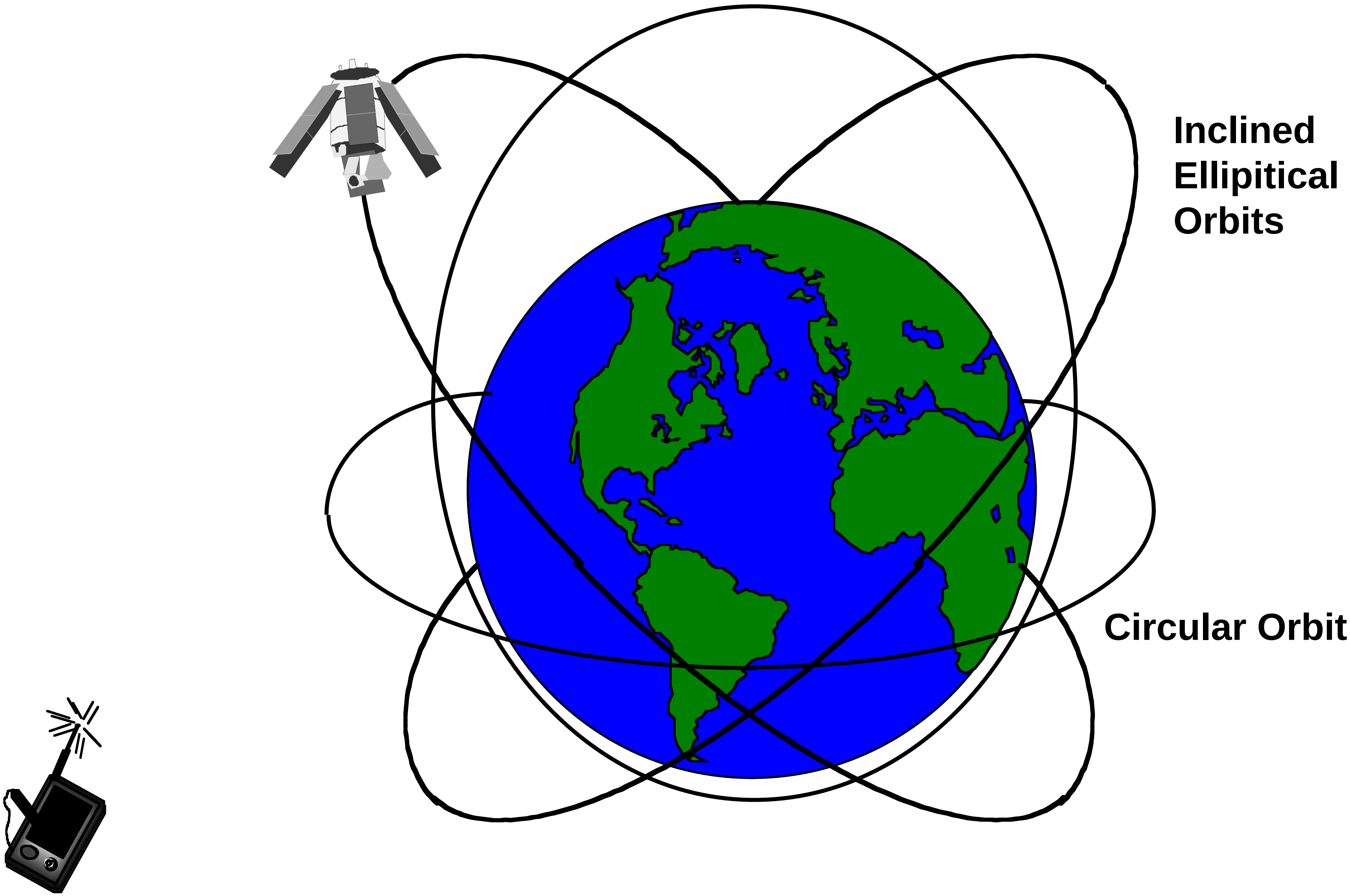
Global Positioning System

- 24 satellites, near circular inclined orbits (20,000 km)
  - 4 satellites yield lat, long, altitude
  - L band transmission: 1575.42 MHz/1227.6 MHz
  - Foot nav error = 10^{-9} s timing error
- Receiver must measure time, from which prop delay and range to satellites in view can be determined
- Satellites broadcast their ephemeris (orbital elements) and the current time in UTC



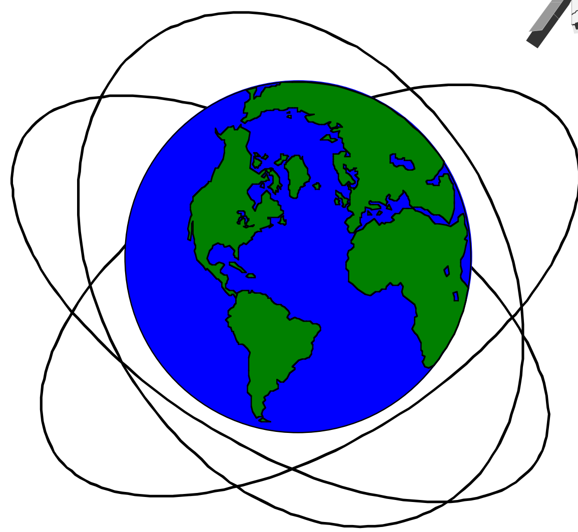


Orbits

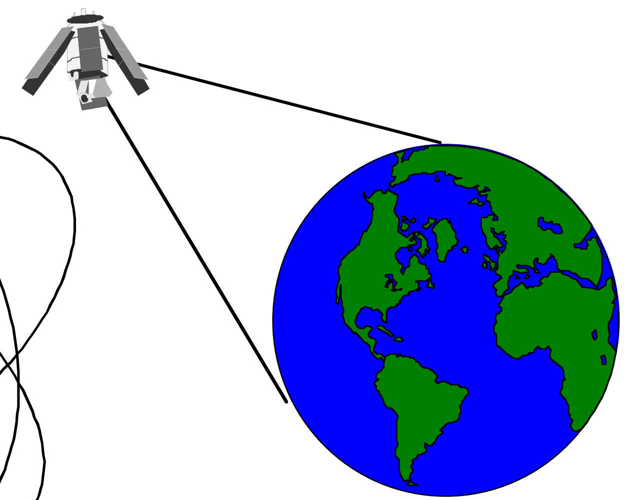


Orbits

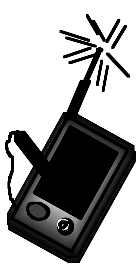
Low Earth Orbits
Height: 100-300 miles
Rotation Period: approx. 90 min.
Time in LOS of
earth station: ≥15 min.



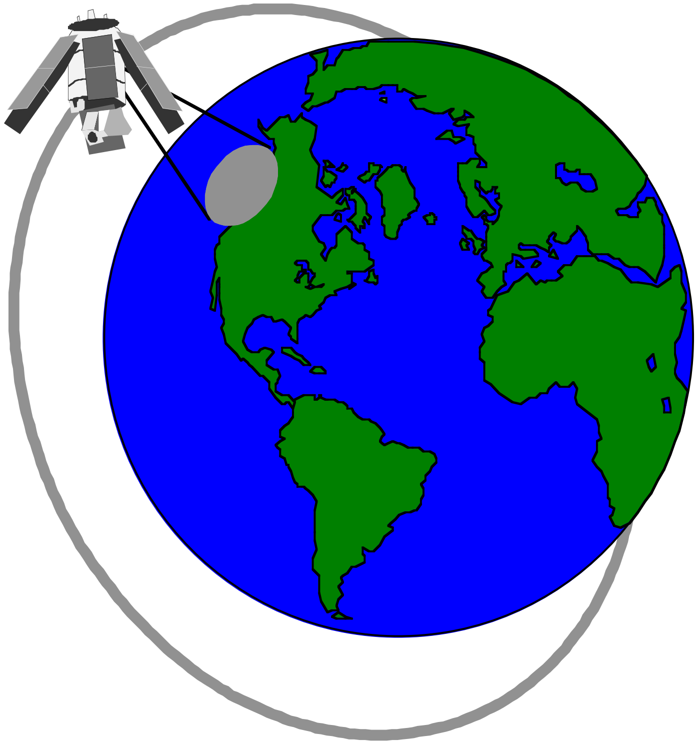
Medium Earth Orbits
Height: 6000-12000 miles
Rotation Period: 5-12 hrs.
Time in LOS of
earth station: 2-4 hrs.

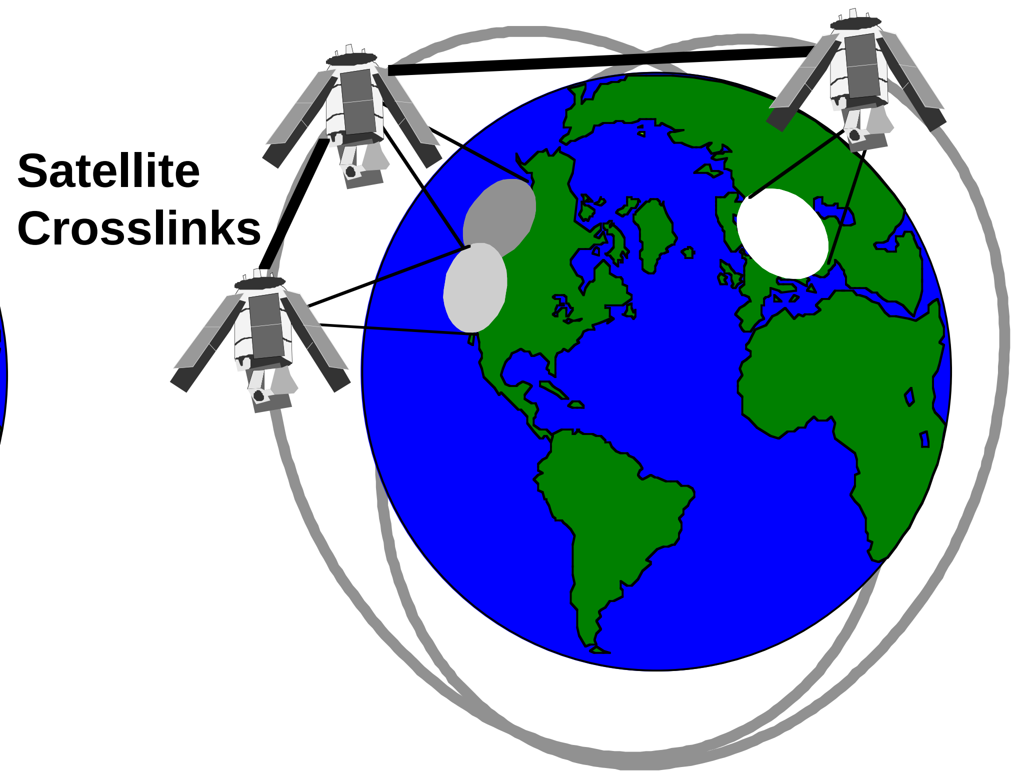


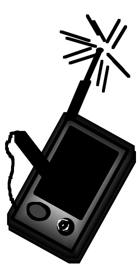
Geosync Orbits
Height: 22,282 miles
Rotation Period: 24 hrs.
Time in LOS of
earth station: 24 hrs.



Satellite Constellation Architectures







Requires ES gateway
within sight of every satellite

Intersatellite links
can reduce the need for
ES gateway coverage

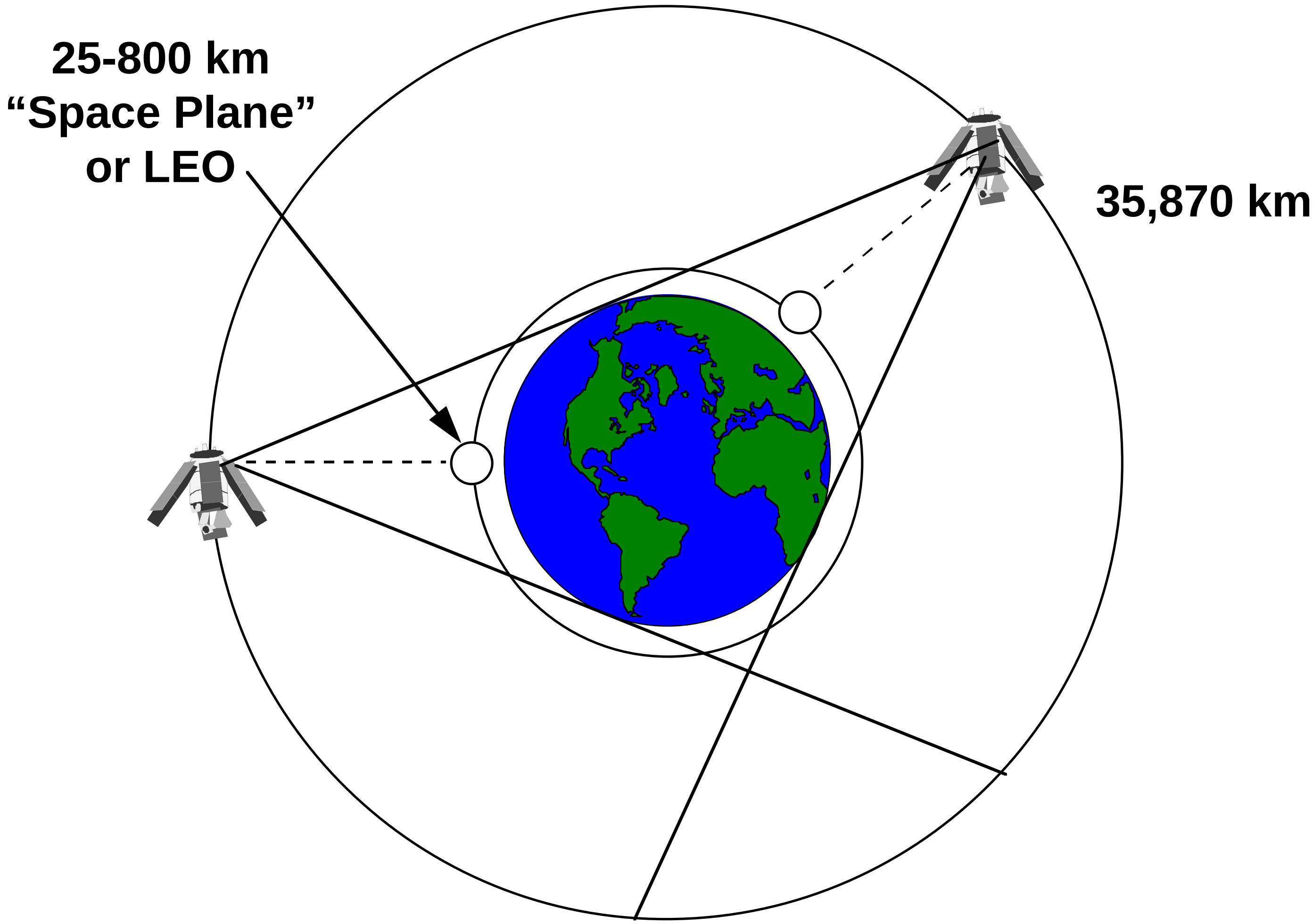
Advantages/Disadvantages with GeoSync

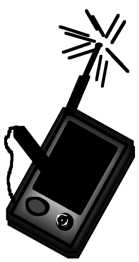
- **Advantages:**
  - Since stationary, requires no ground station tracking
  - No inter-satellite handoff, permanently in view
  - 42.4% of earth surface in view of one satellite
  - Three satellites give full earth coverage
  - Almost no Doppler shift, yields reduced complexity receivers
- **Disadvantages:**
  - 35786 km orbits imply long transmission latencies, on order of 250 ms for one-way, 500 ms round trip
  - Weak received signal (varies with inverse of square of distance)
  - Does not provide good coverage at high latitudes (80 degrees) or urban areas at medium latitudes (40 degrees)

Low Earth Orbit Advantages/Disadvantages

- **Advantages:**
  - Reduced launch costs to place in low Earth orbit (e.g., airplane/ booster launched)
  - Much reduced pass loss, implies lower cost satellite ($0.5-2M)
  - Much shorter transmission delays
- **Disadvantages:**
  - Short visibility from any point on earth demands potentially large constellations (e.g., 15 minutes, with small earth footprint)
  - Satellite lifetime dramatically reduced when in low orbit (e.g., 1-3 months at 300 km orbit)
  - Radiation effects reduce solar cells and electronics lifetimes
    - » Van Allen radiation belts limit orbit placement
    - » Belt 1: 1500-5000 km
    - » Belt 2: 13000-20000 km

High Altitude Long Endurance Platform: Compromise System



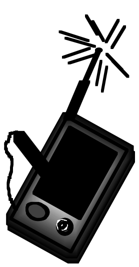


Orbital Considerations

	LEO	MEO	GEO
Van Allen Radiation **Eclipse Interval** **Signal Time Delays** **Spacecraft Elev Angle** **Space Junk**	Low level radiation Frequent day-night cycling 20 ms for 2-way comm Rapidly varying, frequently near horizon Major problem at this orbit	Moderate level radiation Infreq day-night cycling 100 ms for 2-way comm Slowly varying, infrequently near horizon Small # at this orbit	Low level radiation Infreq day-night cycling 250 ms for 2-way comm No variation, near horizon only at high latitudes Moderate at this orbit
# Sats Requires **Cost Sat + Launch** **Sat Lifetime**	Large #, 30-60 Low cost Short, 5 years	Moderate #, 10-20 Moderate cost Long, 10-15 years	Small #, 3-6 High cost Long, 10-15 years
Handoffs/Crosslink **Cost of Ground Seg** **Cost Pers Comms** **Incremental Coverage**	Frequent HO Complex and costly Moderate cost, hi weight Not practical	No HOs/crosslinks Low cost Moderate cost/weight Practical	No HOs/crosslinks Low cost Inexpensive but heavy Very Practical

Comparing the Options

System Type	Sys Cost	Coverage	Beam Thruput	Perf Index
GEO: 3 satellites 8 Beams/7 Year Life	$1.2B	12.6×10^6 km^2	200 Mb	$2834 per mb/km^2/yr
MEO: 12 satellites 20 Beams/5 Year Life	$2B	3.1×10^6 km^2	250 Mb	$6451 per mb/km^2/yr
LEO: 50 satellites 40 Beams/5 Year Life	$4B	1.5×10^6 km^2	50 Mb	$8680 per mb/km^2/yr
Mega LEO: 800 satellites 50 Beams/5 Year Life	$12B	1.5×10^6 km^2	100 Mb	$6000 per mb/km^2/yr
HALE: 12 Cells 10 Year Life	$10 M	0.18×10^6 km^2	200 Mb	$1852 per mb/km^2/yr
Terrestrial 30 Cells/20 Year Life	$50 M	0.008×10^6 km^2	90 Mb	$82,000 per mb/km^2/yr



Index = System Cost/ (Thruput * Beam Size * # Sat * Beams * Life * Eff)
e.g., for LEO, MEO, eff = .3 since 70% of time sat at high lat or over ocean
Costs do not include earth station, which is much higher for GEO

Mobile Satellite Systems

- Geostationary Systems
  - INMARSAT ($15,000 telephone, $5.50/min)
  - MSAT ($2000 telephone, $1.45/min)
- Big “LEO” Systems
  - ARIES
  - ELLIPSO
  - IRIDIUM
  - ODYSSEY
- Little “LEO” Systems
  - Orbcomm
  - LEOSAT
  - STARNET
  - VITASAT

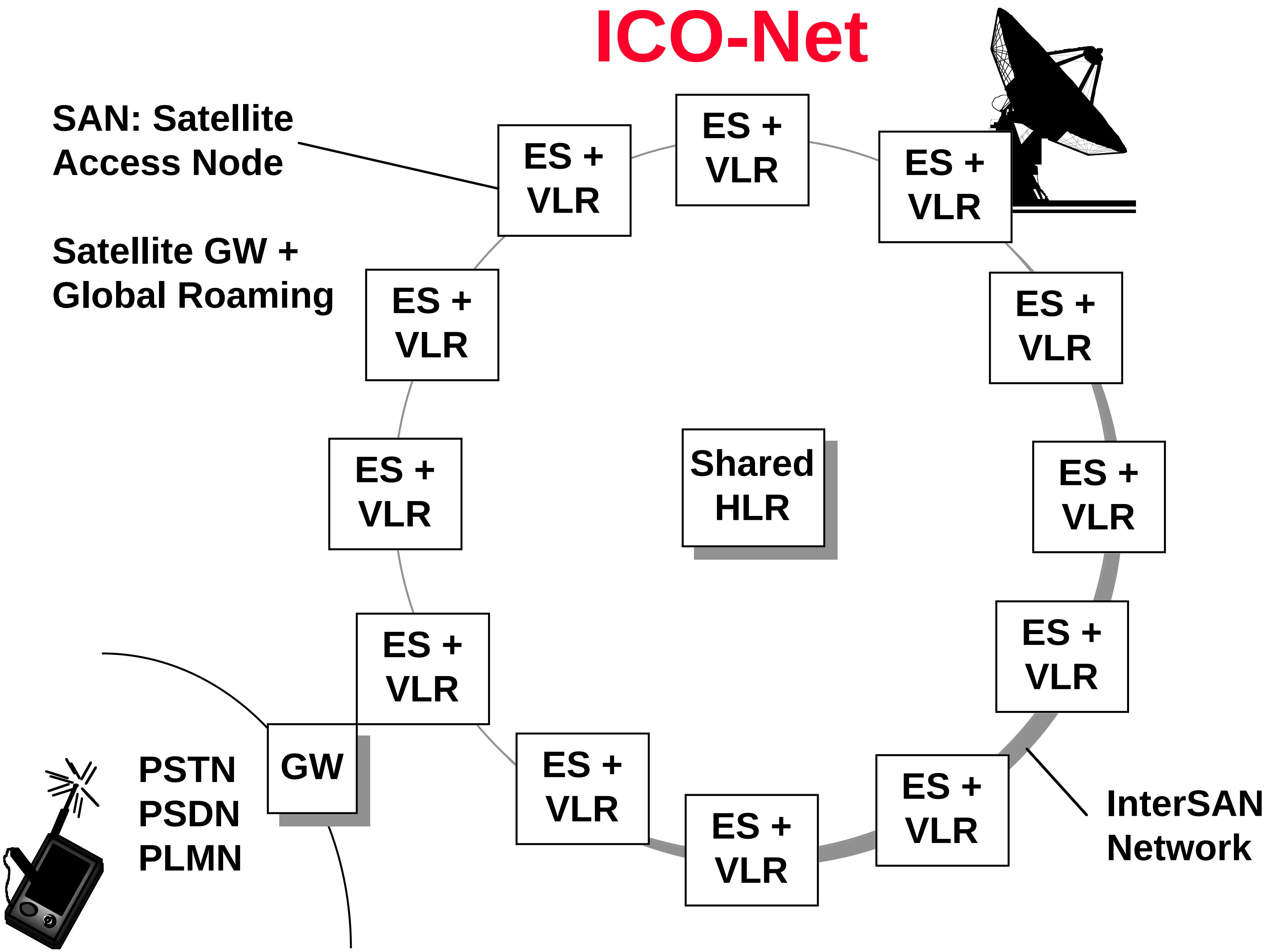
IRIDIUM

- Motorola
- Voice (4.8 kbps), Data (2.4 kbps), Fax, Location Services
- 66 satellites in 6 polar orbits (780 km)
- 48 spot beams per satellite forming “cells” 230 simultaneous duplex conversations
- Satellite-to-satellite links as well as to ground (Ka band@20 GHz to gateways & crosslinks, L band at 1.5GHz to handhelds)
- FDMA uplink, TDM downlink
- Supports satellite handoff during calls

ICO Global Communications

- **Funded by Inmarsat, Hughes to build the satellites**
- **ICO = Intermediate Circular Orbit (8-10,000 km)**
  - **6-20 satellites to cover earth, vs. 40-70 for LEO and 3-6 for GEO**
  - **200 ms propagation delay**
  - **High average elevation angle from user to satellite (>40 degrees)**
  - **High probability of visibility from more than one satellite, yields path diversity (70% of each footprint overlaps with another satellite)**
  - **Relatively slow moving satellites (1 degree per minute)**
  - **Minimum requirements for establishing a connection:**
    - » **ES can see satellite 5 degrees above horizon**
    - » **User can see satellite 10 degrees above horizon**
  - **TDMA, 4500 (750 carrier waves) telephone channels per satellite**

ICO-Net


SAN: Satellite Access Node
Satellite GW + Global Roaming
ES + VLR
ES + VLR
ES + VLR
ES + VLR
ES + VLR
ES + VLR
ES + VLR
ES + VLR
ES + VLR
ES + VLR
ES + VLR
ES + VLR
Shared HLR
GW
PSTN
PSDN
PLMN
InterSAN Network

ODYSSEY

- TRW
- Voice, Data (9.6 kbps), Fax, Location Services
- 12 satellites, 4 in each of 3 orbital planes
  3000 voice circuits per satellite
- Medium earth orbit: 10370 km
- CDMA access techniques
- No handover between satellites, because of long satellite visibility from ground
- Steering antenna scheme also eliminates need for spot beam handovers

GLOBALSTAR

- Loral, Qualcomm
- Voice, Data (9.6 kbps), Fax, Location Services
- 48 satellites (8 spares), inclined orbits, 1400 km
- No satellite handovers, elliptical spot beams (6 per sat) insure long coverage of mobile user
- CDMA access techniques

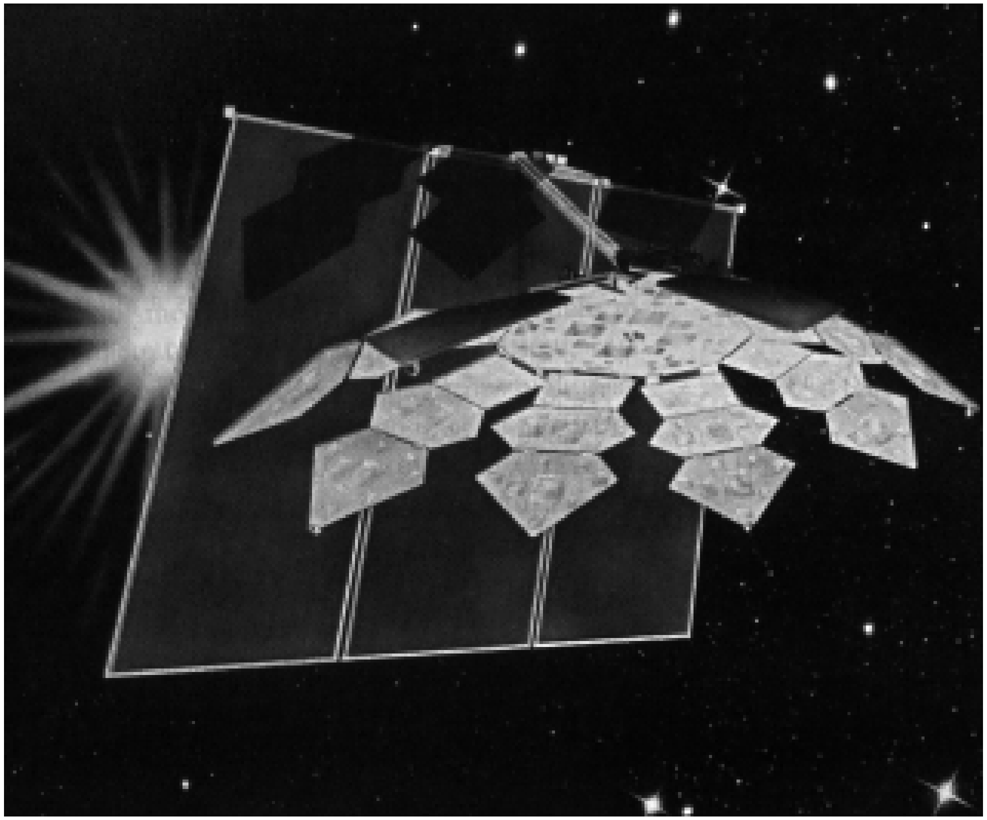
- ARIES, similar proposal from Consellation
- ELLIPSO, 15 satellites in elliptical orbit (reach apogee over mid latitudes of northern hemisphere) plus 9 in equalitorial circular orbits to cover rest of the world

Teledesic

- Major Investors: Bill Gates. Craig McCaw
- 21 orbital planes, 40 satellites per plane, 840 satellites total(!!)—$9 billion to deploy
- 700 km, circular orbits, high elevations
- 20 Ghz Ka band, large number of satellites mitigates rain attenuation problems
- Hand held communicators can see two satellites at all times: soft handoff, load sharing
- Voice/Data up to 2 Mbps

Teledesic

- **Unique flower-shaped satellite with sophisticated phase array antennas**



Mobile Satellite Systems

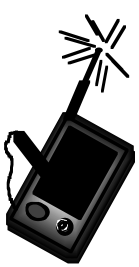
SYSTEM	INMARSAT M	MOBILSAT	ODYSSEY	IRIDIUM	GLOBAL-STAR	ARIES	ELLIPSO	ORBCOMM
Applicant	Comsat, etc.	AMSC	TRW	Iridium, Inc.	Loral Qualcomm	Constellation	Ellipsat Corp.	Orbital Sciences
System Type	Geosatellite	Geosatellite	Meosatellite	Big Leo Sat	Big Leo Sat	Big Leo Sat	Big Leo Sat	Little Leo Sat
Purpose	Voice, Data	Voice, Data	Voice, Data	Voice	Voice			Data, Paging
Vendors, Partners	Magnavox, etc.	Hughes, Telesat	TRW	Motorola, etc.	RBOCs, PTTs	Constell Comms	Harris, Fairchild	Champion, etc.
Type of Portable Formfactor	Briefcase	Pocket Telephone	Pocket Telephone	Pocket Telephone	Pocket Telephone			Handheld Data Terminal
Fixed Infra-structure Needed	Gateways	Gateways	Gateways	Gateways	Gateways			Gateways
Comm Type	Digital	Digital	Digital	Digital	Digital			Digital
Geographic Coverage	Worldwide	N. America	Worldwide	Worldwide	Worldwide			Worldwide

Mobile Satellite Systems

SYSTEM	INMARSAT M	MOBILSAT	ODYSSEY	IRIDIUM	GLOBAL-STAR	ARIES	ELLIPSO	ORBCOMM
Two-Way	Yes	Yes	Yes	Yes	Yes			Yes
PSTN Access	Yes	Yes	Yes	Yes	Yes			via PDNs
# of Satellites	4	2	9 to 12	66	48	48	6, then 24	26
Orb Alt (km)	36,000	36,000	10,370	780	1414	1020	580/7800	765
Orb Type/Locs	18,55W; 63W, 139W	62W, 139W		Pol			Elliptical	
Launch Date	1980s	1995	1998	1996				1996
Service Date	1988	1996	1999	1998	1997			1997
Freq Band	L-Band	L-Band	L-Band	L-Band	L-Band	L-Band	L-Band	UHF, VHF

Mobile Satellite Systems

SYSTEM	INMARSAT M	MOBILSAT	ODYSSEY	IRIDIUM	GLOBAL-STAR	ARIES	ELLIPSO	ORBCOMM
Frequencies	1.6 GHz	1.6-1.7 GHz	1.6, 2.4 GHz	1.6, 2.4 GHz	1.6, 2.4 GHz	1.6, 2.4 GHz	1.6, 2.4 GHz	137, 149, 400 MHz
Access Method	FDMA	FDMA	FDMA/ CDMA	FDMA/ TDMA	FDMA/ CDMA	CDMA	CDMA	
Latency (2-way)	500 ms (rt)	500 ms (rt)	~120 ms (rt)	~10 ms (rt)	~10 ms (rt)			~10 ms (rt)
Price (Handheld)	$20-30,000	$2-4,000	$250-450	$200-2000	$700-1000	$1500	$600	$50-350
Price (Airtime)	~$5.50/min	$1.50/min	$0.65/min	$3.00/min	$0.30/min	$30.00/ month	$0.50/min	$50.00/month



System Summary

	Odyssey	ICO	Globalstar	Constellation
Service Type	Voice, data, fax, paging, messaging	Voice, data, fax, paging, messaging, pos location	Voice, data, fax, paging, video	Voice, data, fax
Voice (kbps)	4.8	4.8	Adaptive 2.4/4.8/9.6	4.8
Data (kbps)	9.6	2.4	7.2	2.4
System cost	$1.8B	$2.6B	$2.0B	$1.7B
User terminal cost	$300	"Several Hundred"	$750	N/A
Satellite Lifetime	10 years	10 years	7.5 years	N/A
Call rates (per min)	$0.65	$1.00-2.00	$0.35-0.55	N/A
Ops scheduled	2000	2000	1998	1998
# of Satellites	12 + 3 spares	10 + 2 spares	48 + 8 spares	36
Multiaccess method	CDMA	TDMA	CDMA	CDMA
Investors	TRW, Teleglobe	INMARSAT, Hughes Space	Loral-Qualcomm, AirTouch, Vodafone, Deutche Aerospace, Dacom	Orbital Sciences, Teleglobe

System Summary

	Iridium	Teledesic	Ellipso
Service Type	Voice, data, fax, paging, video	Voice, data, fax, paging,	Voice, data, fax, paging, video, pos location
Voice (kbps)	2.4/4.8	16.0	4.2
Data (kbps)	2.4	16.0-2048.0	0.3-9.6
System cost	$3.7B	$9.0B	$750M
User terminal cost	$2500-3000	N/A	$1000
Satellite Lifetime	5 years	10 years	5 years
Call rates (per min)	$3.00	N/A	0.50
Ops scheduled	1998	2002	1998
# of Satellites	66 + 6 spares	840 + 84 spares	10 + 6 spares
Multiaccess metho	FDMA, TDMA, TDD	TDMA, SDMA, FDMA, ATDMA	CDMA
Investors	Motorola, Raytheon, Great Wall Ind, Khrunichev Entr., Kyocera, Mitsui, Mawadi Group	Gates, McCaw	Westinghouse, Harris, Israeli Aircraft Ind.