INTRODUCTION TO SATELLITE COMMUNICATION

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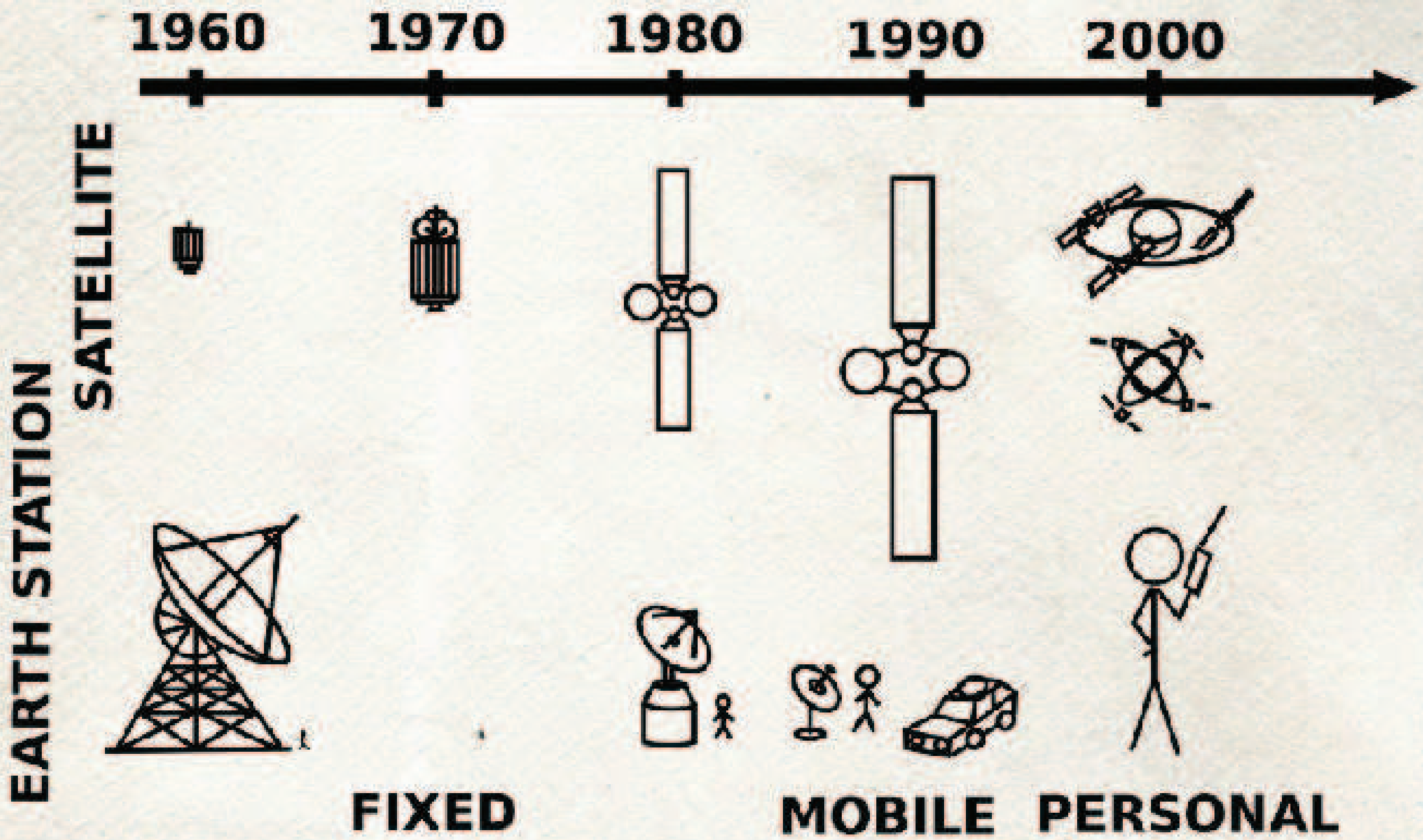
CHAOS COMMUNICATION CAMP 2011

SATELLITE HISTORY I

- 1945+ "IMAGINATION"
- INVENTION OF THE TRANSISTOR, SOLAR CELLS AND THE TRAVELLING-WAVE-TUBE AMPLIFIER
- OCT 4^{TH} 1957 - SPUTNIK 1
- FEB 1^{ST} 1958 - EXPLORER 1 "EARLY BIRD",
- 1960 - COURIER 1B: 1^{ST} SOLAR-CELL POWERED SATELLITE
- 1964 - SAN MARCO 1, ITALY ...

SATELLITE HISTORY II



SATELLITE SUBSYSTEMS I

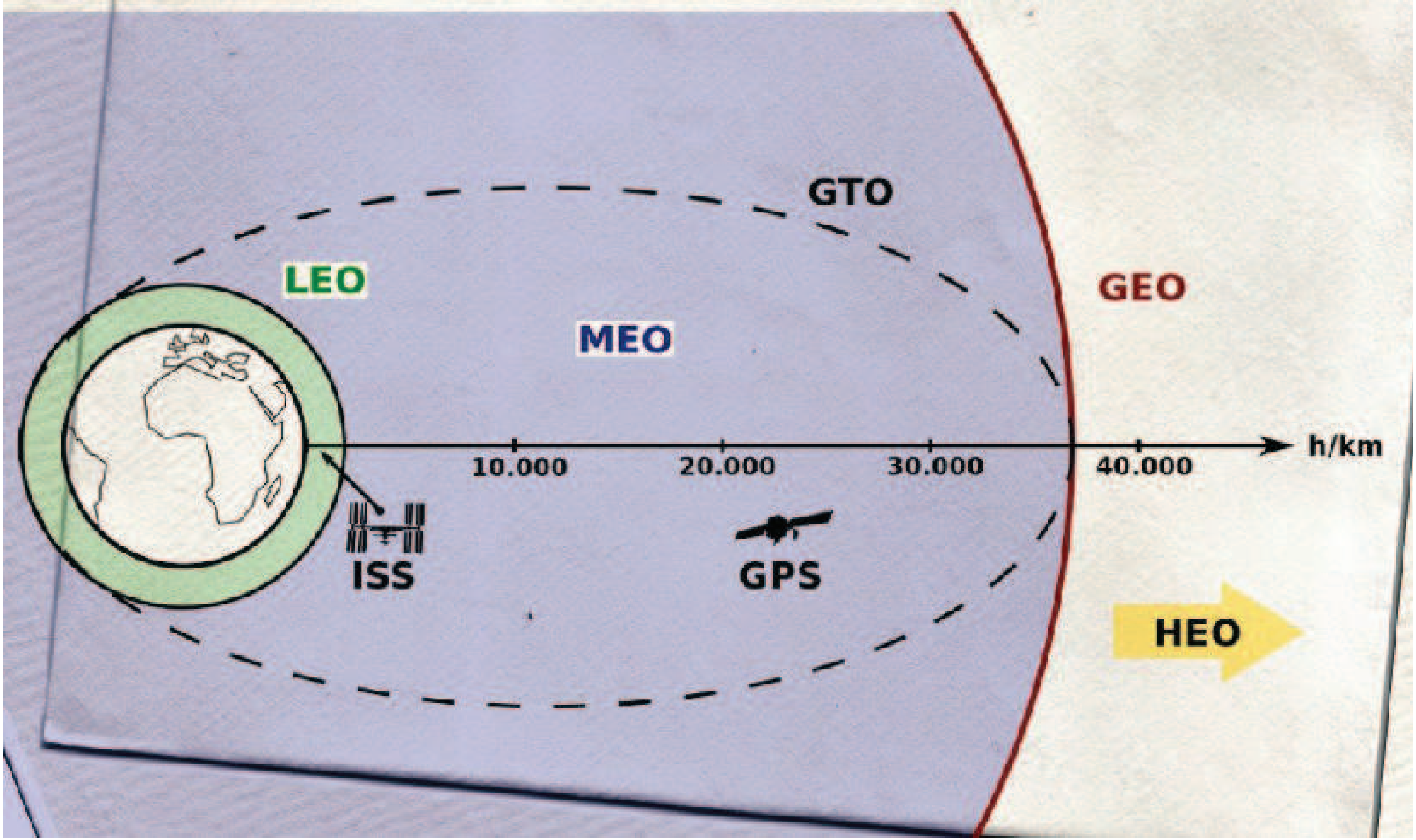
- STRUCTURE
  - PLATFORM (BUS) CARRYING PAYLOAD
  - SPIN VS. THREE AXIS STABILIZATION
- PROPULSION SYSTEM
  - LOW POWER THRUSTERS (ORBIT CONTROL)
  - MEDIUM AND HIGH POWER THRUSTERS
  - CHEMICAL & ELECTRIC PROPULSION
- AOC - ATTITUDE AND ORBIT CONTROL
  - STEERING, STABILIZATION, ATTITUDE SENSORS, ACTUATORS

SATELLITE SUBSYSTEMS II

- POWER SUPPLY
  - DIRECTLY RELATED TO RF POWER OF THE PAYLOAD AMPLIFIERS
  - PRIMARY SOURCE: SOLAR GENERATOR
  - SECONDARY SOURCE: ACCUMULATORS
- TT&C – TELEMETRY, TRACKING AND COMMAND
  - ALLOCATED FREQUENCY BANDS
  - VITAL
- THERMAL CONTROL

COMMUNICATIONS PAYLOAD

SATELLITE ORBITS I



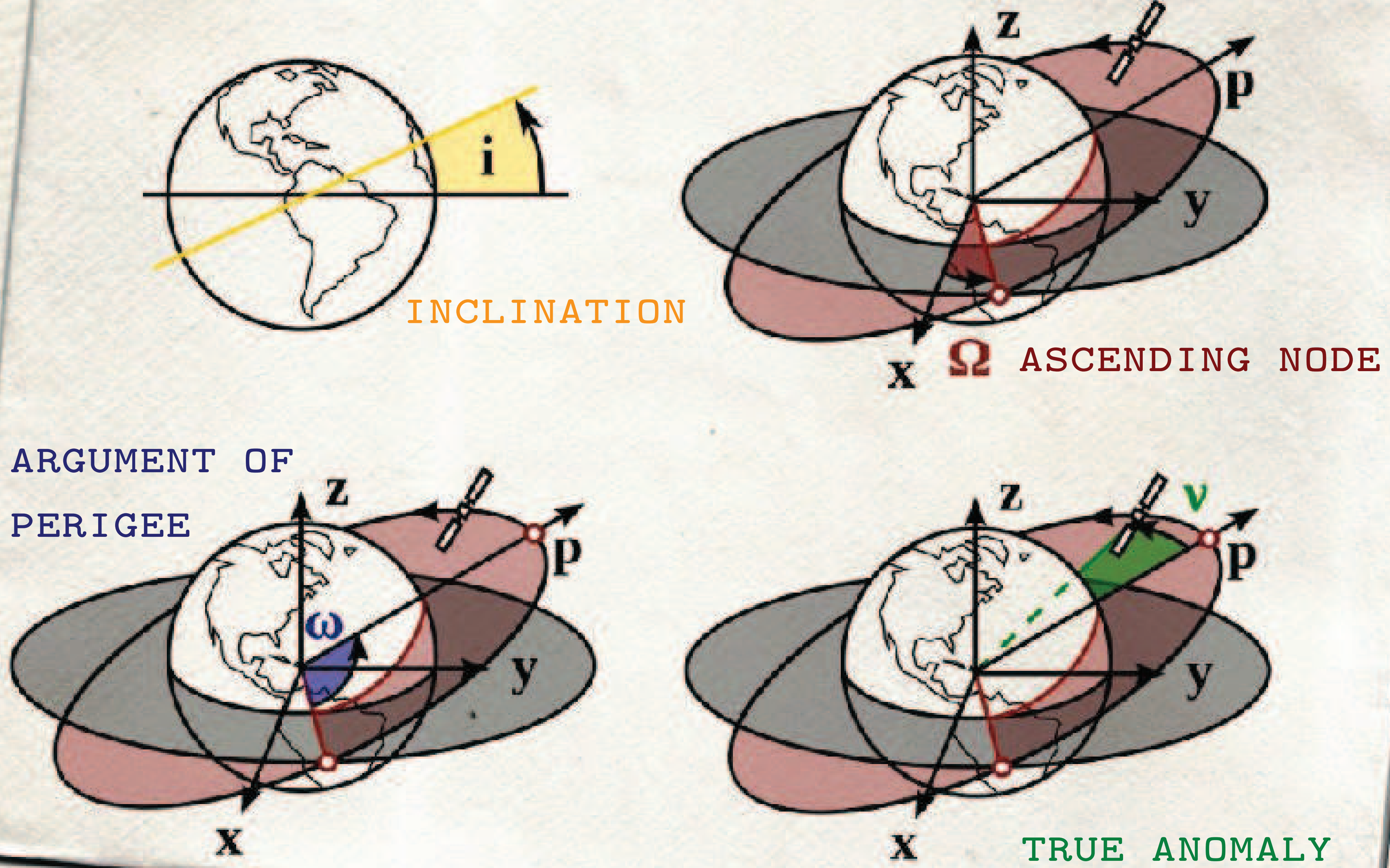
SATELLITE ORBITS II

- CIRCULAR & ELLIPTICAL
- INCLINATION
- GEOSYNCHRONOUS OR NOT
- GEOSTATIONARY
- PROGRADE & RETROGRADE
  - MOST SATELLITES MOVE EASTWARDS

ANGULAR SPEED OF EARTH $\omega_E = \frac{2\pi}{T_{SID}} = 4.178 \cdot 10^{-3} \,°/s$

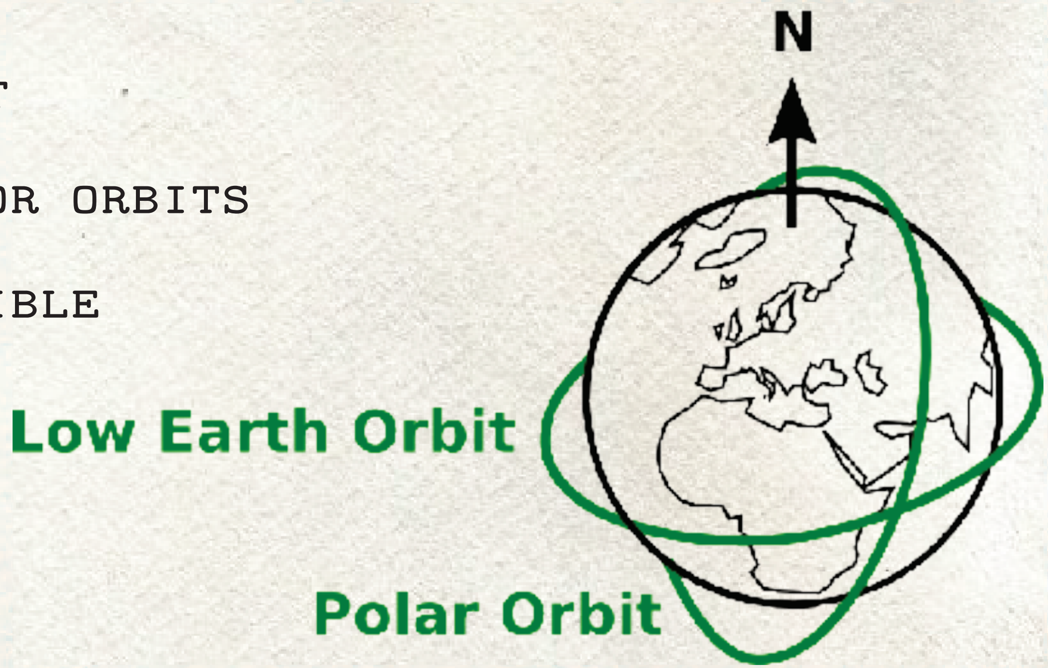
→ VELOCITY AT EQUATOR $v_0 = \omega_E \cdot r_E = 1674\, km/h$

ORBITAL PARAMETERS



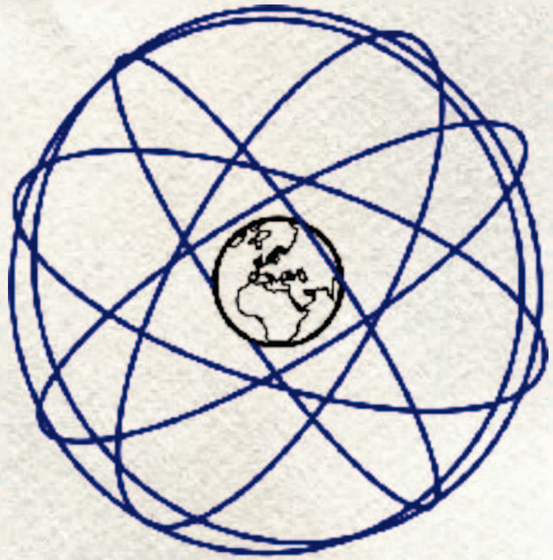
LOW EARTH ORBIT

- H ~ 500 - 2000 KM T ~ 2H
- MOBILE PERSONAL COMMUNICATIONS SERVICES
  - IRIDIUM, GLOBALSTAR, ORBCOMM
- ADVANTAGES
  - IMPROVED POWER BUDGET
  - MANY POSSIBILITIES FOR ORBITS
  - POLAR REGIONS ACCESSIBLE
- DISADVANTAGES
  - TRACKING REQUIRED
  - SPACE DEBRIS



MEDIUM EARTH ORBIT

- BETWEEN LEO AND GEO $T \sim 6$ H
- NAVIGATION SATELLITES $H \sim 20\,000$ KM
  - GPS, GLONASS, GALILEO
- ADVANTAGES
  - LARGER COVERAGE AREA
  - LESS ATMOSPHERIC DRAG THAN LEO
- DISADVANTAGES
  - HIGHER LATENCY
    BUT: *TOA* USED FOR NAVIGATION



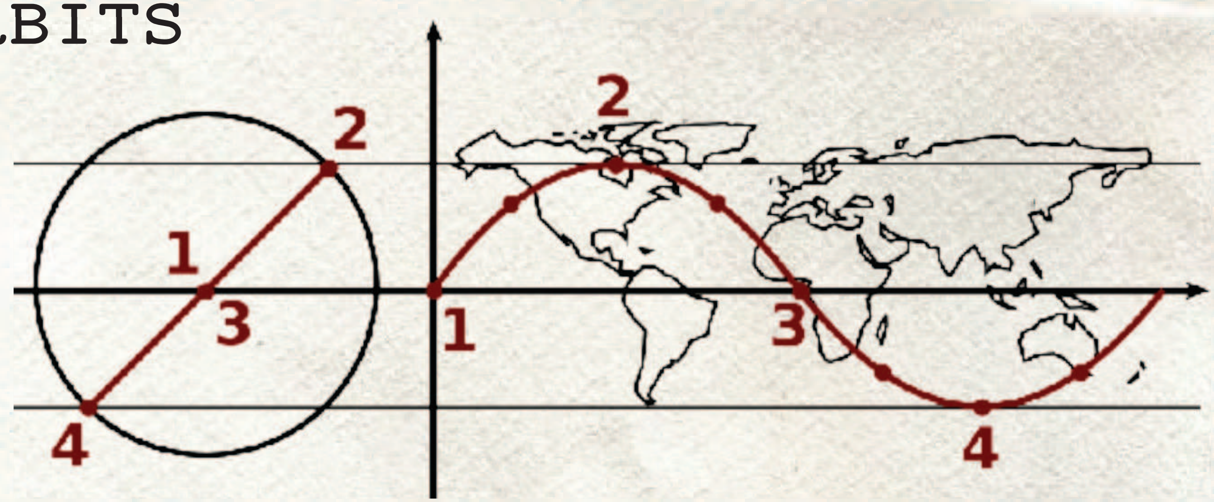
GPS Medium
Earth Orbits

CIRCULAR ORBITS

- CIRCULAR ORBIT

  I = 45°

  T = TSID



- GRAVITATIONAL FORCE OF ATTRACTION: $F_G = G\dfrac{m_E m_S}{r^2}$

- CENTRIFUGAL FORCE: $F_C = m_S \dfrac{v_o^2}{r}$ $F_G = F_C$

$$\rightarrow \quad T_{orb} = 2\pi\sqrt{\frac{r^3}{G m_E}} \qquad h_E = r - R_E = \sqrt[3]{\frac{G m_e T_{orb}^2}{4\pi^2}} - R_E$$

$$v_o = \frac{2\pi r}{T_{orb}} = \sqrt{\frac{G m_E}{r}}$$

GEOSTATIONARY ORBIT I

- $\omega_S = \omega_E$
- SATELLITE ORBIT $\in$ EQUATORIAL PLANE

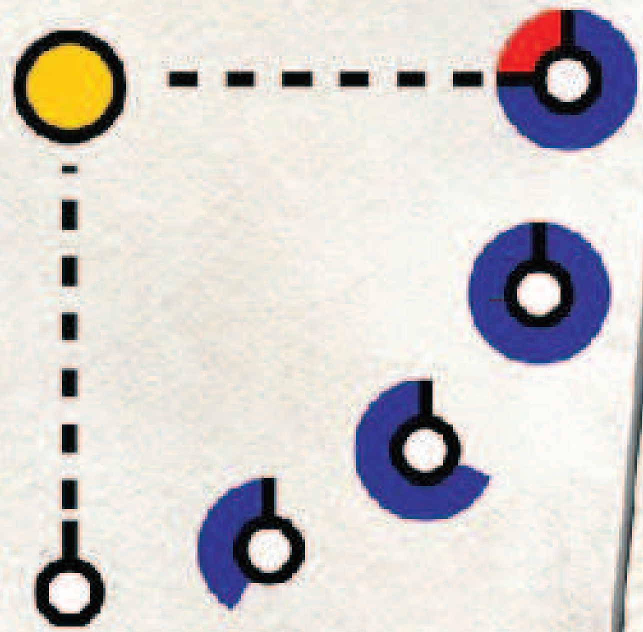
FIXED SUBSATELLITE POINT

- SIDEREAL DAY:

$$T_{sid} = \frac{365.25}{365.25+1} \cdot 24\mathrm{h} = 23\mathrm{h}\,56\mathrm{min}\,4\mathrm{s}$$

→ HEIGHT OF GEO SATELLITE:

$$(h_E)_{geo} = \sqrt[3]{\frac{G\, m_E\, T_{sid}^2}{4\pi^2}} - R_E = 35786\,km$$

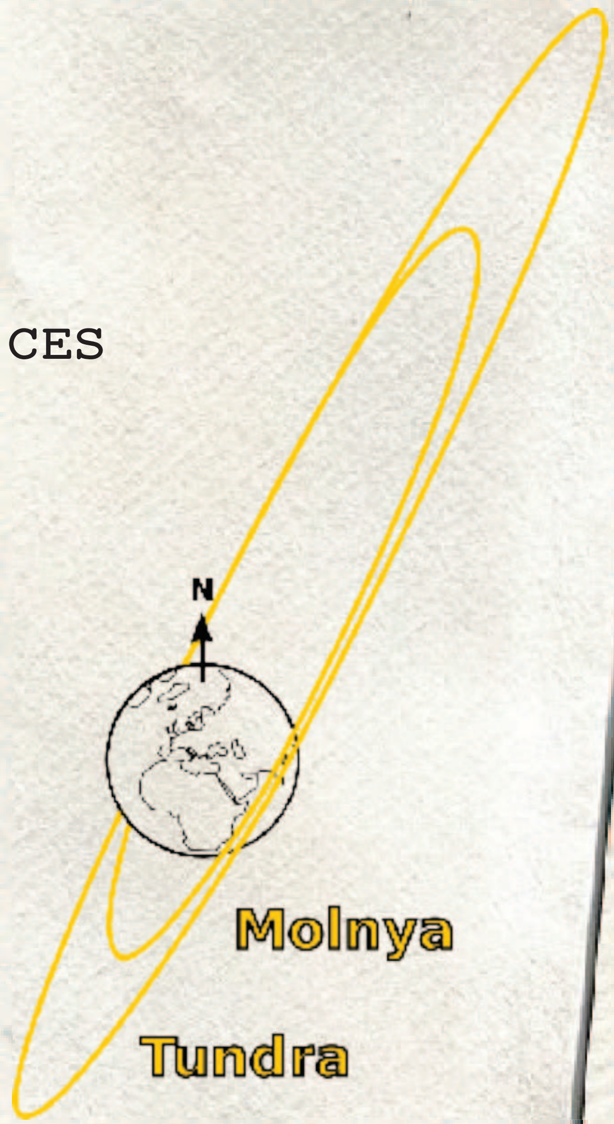


GEOSTATIONARY ORBIT II

- ADVANTAGES
  - FIXED SUBSATELLITE POINT
  - NO TRACKING REQUIRED (IN THEORY)
  - FEW SATELLITES REQUIRED FOR GLOBAL COVERAGE
  - HIGHER LIFETIME
- DISADVANTAGES
  - CROWDED
  - POLAR REGIONS NOT ACCESSIBLE
  - ECLIPSES

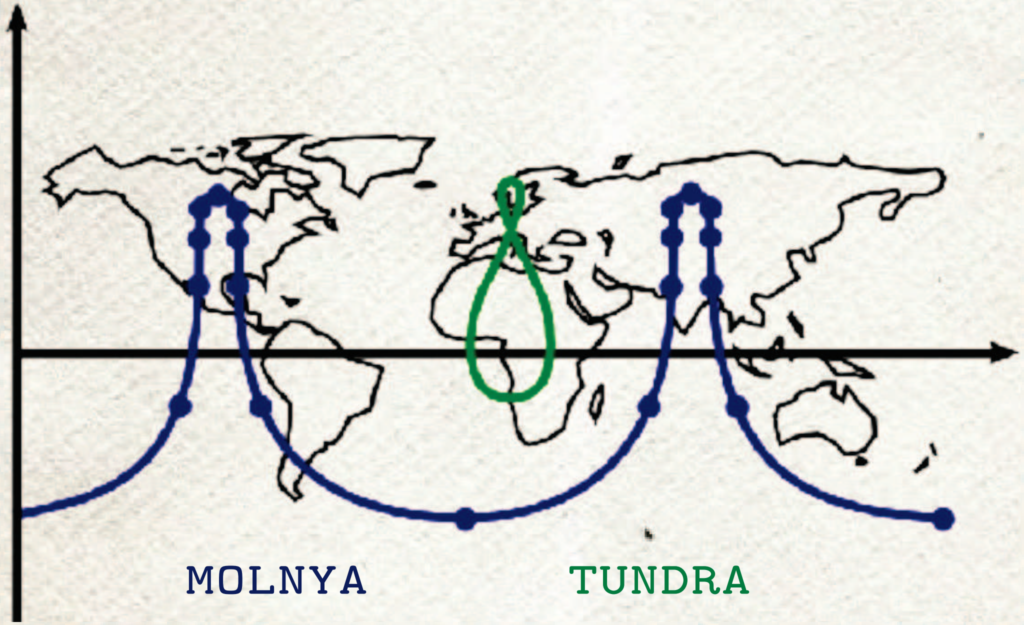
HIGHLY ELLIPTICAL ORBITS I

- MOLNYA ORBIT
  - $T = T_{SID}/2$ $I = 63.4°$
    $P \sim 1\,200$ KM $A \sim 40\,000$ KM
  - COMMUNICATION AND BROADCAST SERVICES FOR AREAS WITH HIGH LATITUDE
- TUNDRA ORBIT
  - $T = T_{SID}$ $I = 63.4°$
    $P \sim 25\,000$ KM $A \sim 46\,000$ KM
  - BROADCAST SERVICES FOR CONFINED AREAS



HIGHLY ELLIPTICAL ORBITS II

- ADVANTAGES
  - APOGEE DWELL →
    SERVICES FOR DEFINED REGIONS



- DISADVANTAGES
  - VARYING DOPPLER SHIFTS
  - MOLNYA: CROSSING VAN-ALLEN BELTS 4x A DAY

ORBITAL PERTURBATIONS

- ASYMMETRIC SHAPE OF THE EARTH
  - FLATTENING OF POLES → $\dfrac{d\Omega}{dt}$, $\dfrac{d\omega}{dt}$
  - DIFFERENT EQUATORIAL RADIUS

    → EAST/WEST STATION KEEPING

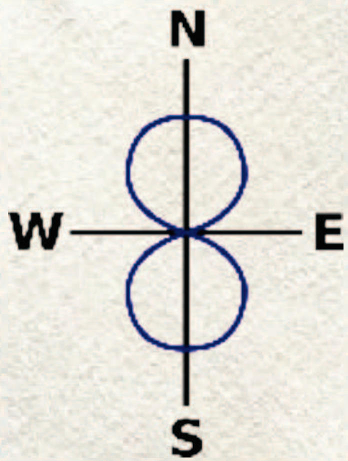
- ATMOSPHERIC DRAG

  → DECREASE OF SEMI-MAJOR AXIS

- ATTRACTION OF SUN AND MOON

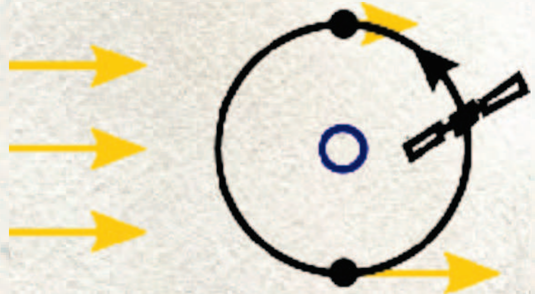
  "8"-SHAPED PATH OF GEO-SATELLITE

  → NORTH/SOUTH STATION KEEPING



- SOLAR RADIATION PRESSURE

  → ORBIT BECOMES MORE ELLIPTICAL



MAGNETOSPHERE

- PROTECTS EARTH FROM SOLAR WIND AND COSMIC RADIATION
- VAN ALLEN BELTS
  - OUTER: 13 000 - 65000 KM
    INNER: 700 - 10000 KM
  - INTEGRATED CIRCUITS AND SENSORS CAN BE DAMAGED
  - SOLAR CELL PERFORMANCE DEGRADES
  - MINIATURIZATION MAKES ELECTRONICS MORE VULNERABLE TO RADIATION

DECIBEL

- VALUE IN DB DESCRIBES A RATIO

$$P_{[dB]} = 10 \cdot \log_{10} \frac{P_{out}}{P_{in}} \qquad \frac{P_{out}}{P_{in}} = 10^{\frac{P_{[dB]}}{10}}$$

- ABSOLUTE VALUES → REFERENCE

$$P_{[dBm]} = 10 \cdot \log_{10} \frac{P}{1\mathrm{mW}} \qquad P_{[dBw]} = 10 \cdot \log_{10} \frac{P}{1\mathrm{W}}$$

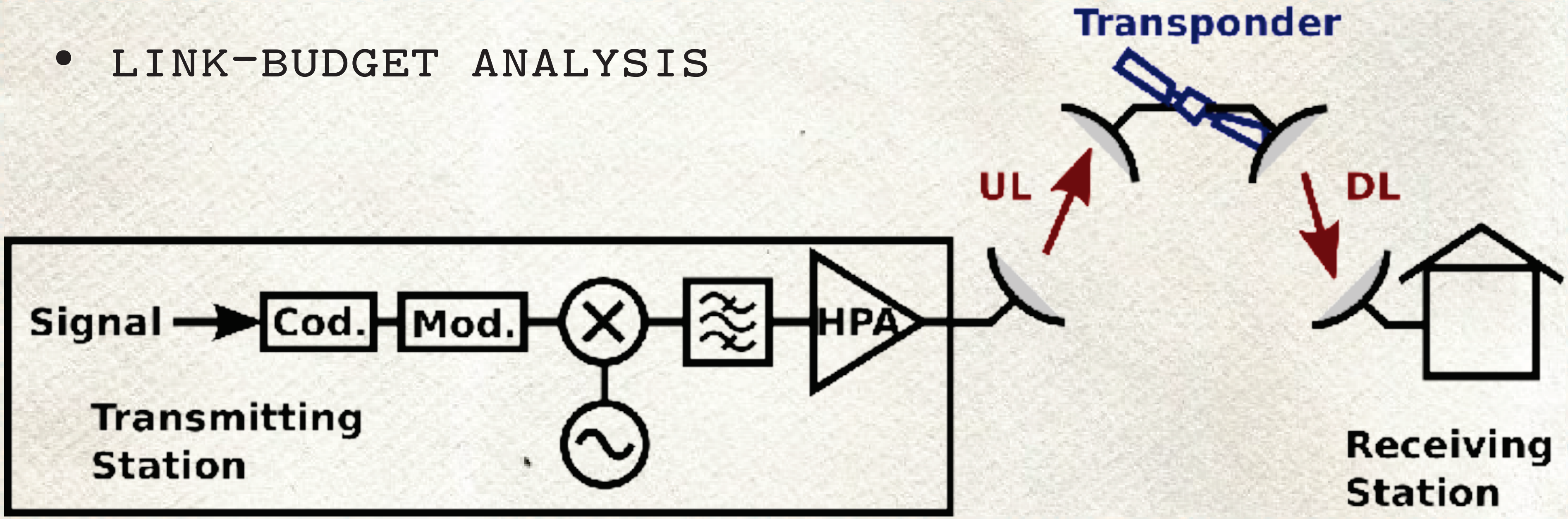
P	10^n	100	10	5	2	1
P[dB]	n x 10	20	10	~ 7	~ 3	0

P	1	1/2	1/5	1/10	1/100	10^-n
P[dB]	0	~ - 3	~ - 7	- 10	- 20	- n x 10

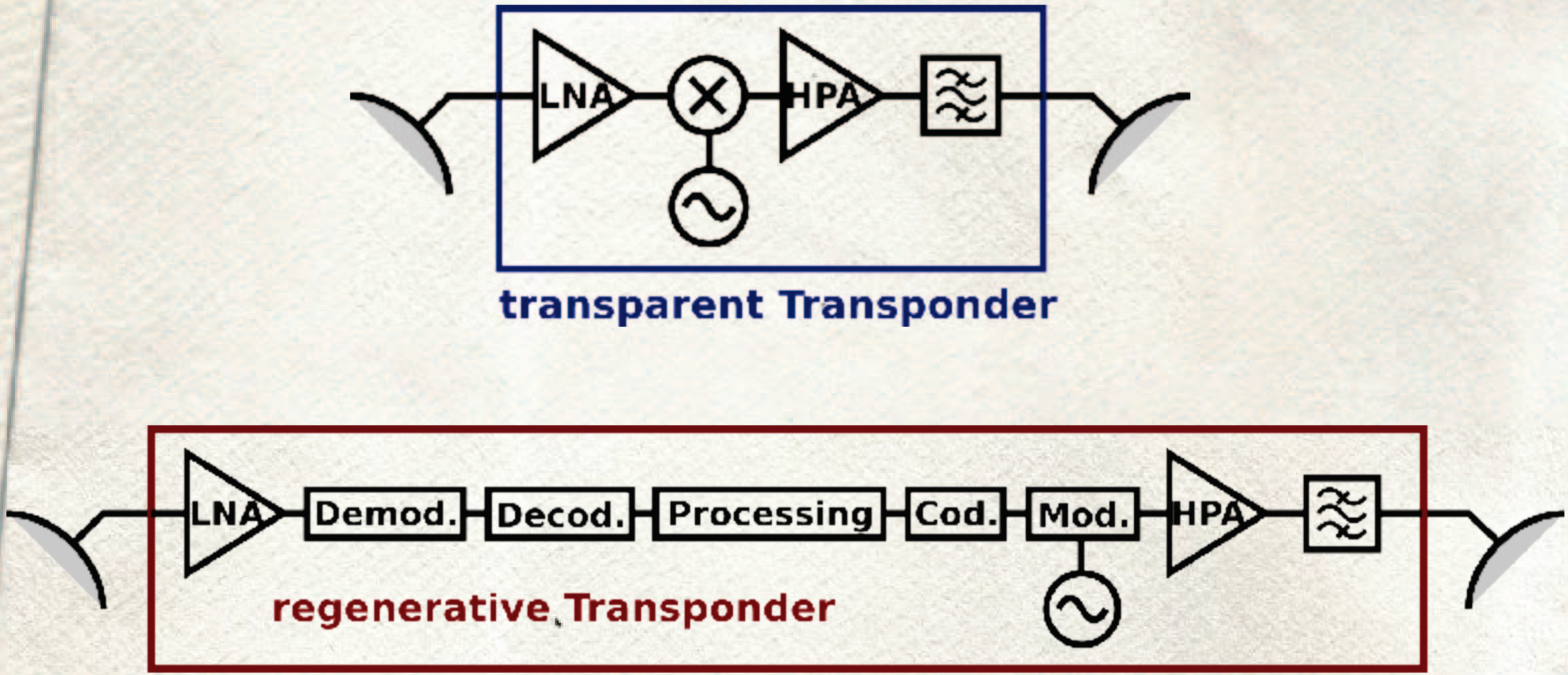
$$\log(a \cdot b) = \log(a) + \log(b)$$
$$\log(a/b) = \log(a) - \log(b)$$

SATELLITE COMMUNICATIONS LINK

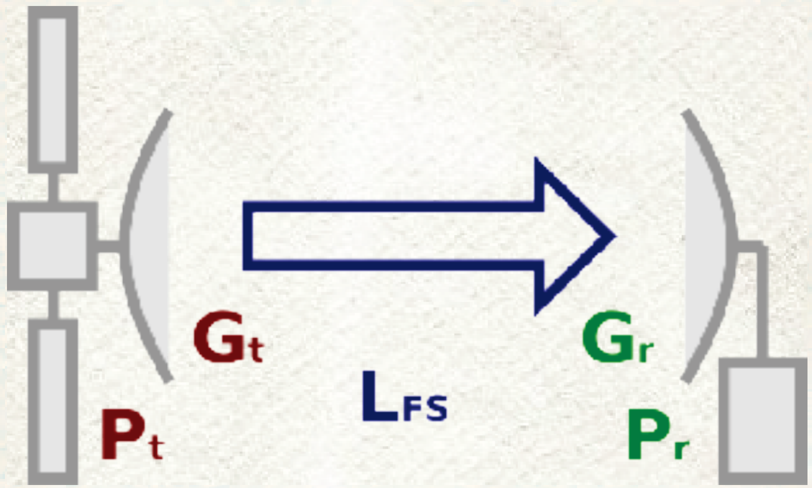
- NETWORK ARCHITECTURES
- STATION-TO-STATION LINK
- LINK-BUDGET ANALYSIS



TRANSPONDERS



LINK BUDGET



- RECEIVED POWER $$P_R = P_T G_T \frac{G_R}{L_{FS}}$$

  IN DB: $$P_{R,dB} = P_{T,dB} + G_{R,dB} + G_{T,dB} - L_{FS,dB}$$

- FREE SPACE LOSS $$L_{FS} = \left(\frac{4\pi R}{\lambda}\right)^2 = \left(\frac{4\pi R f}{c}\right)^2$$

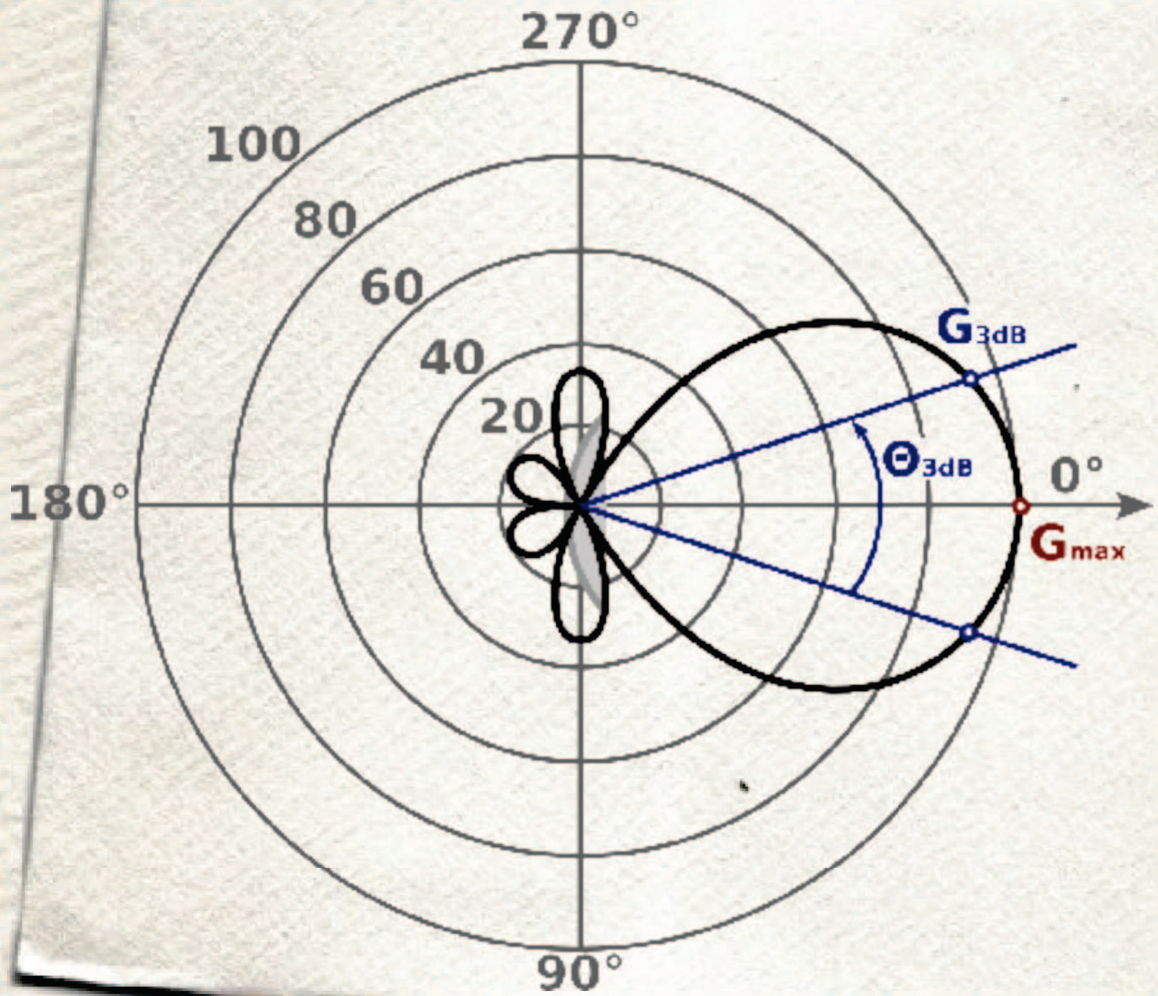
ANTENNAS I

- ISOTROPIC RADIATOR
  - HYPOTHETICAL ANTENNA UNIFORMLY DISTRIBUTES ENERGY IN ALL DIRECTIONS
  - SURFACE POWER DENSITY $S_K = \dfrac{P_T}{4\pi r^2}$
- EIRP: EQUIVALENT ISOTROPIC RADIATED POWER

$$EIRP = P_T G_T$$

  - GAIN DESCRIBES DIRECTIVITY IN COMPARISON TO AN ISOTROPIC RADIATOR
  - EXAMPLE: $P_{T,A} = 2x P_{T,IR} \rightarrow G_A = 3\text{dBi}$

ANTENNAS II



APERTURE ANTENNA

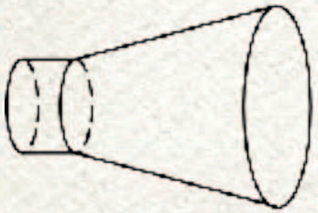
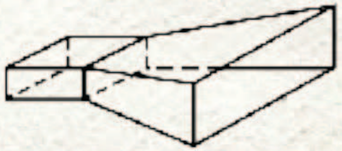
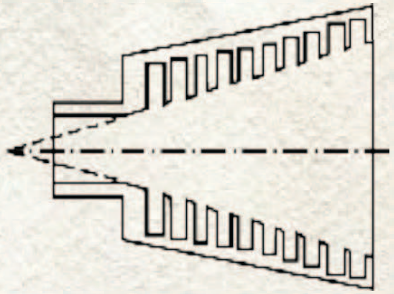
$$G(\theta,\phi) = \frac{4\pi P(\theta,\phi)}{P_T}$$

$$G_{max} = \frac{4\pi A_{eff}}{\lambda^2}$$

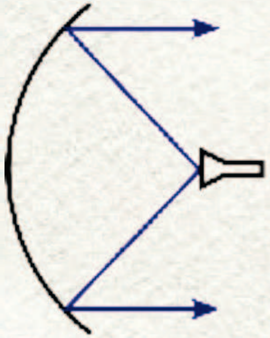
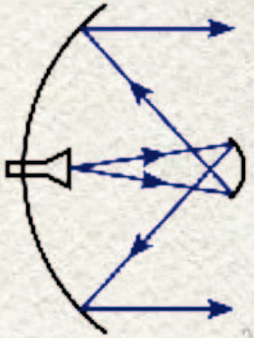
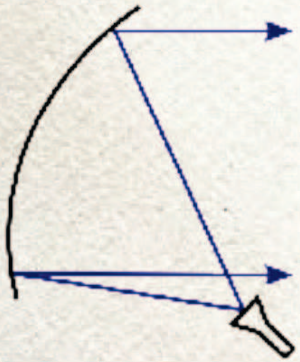
$$A_{eff} = A\eta \qquad \lambda = \frac{f}{c}$$

ANTENNAS III

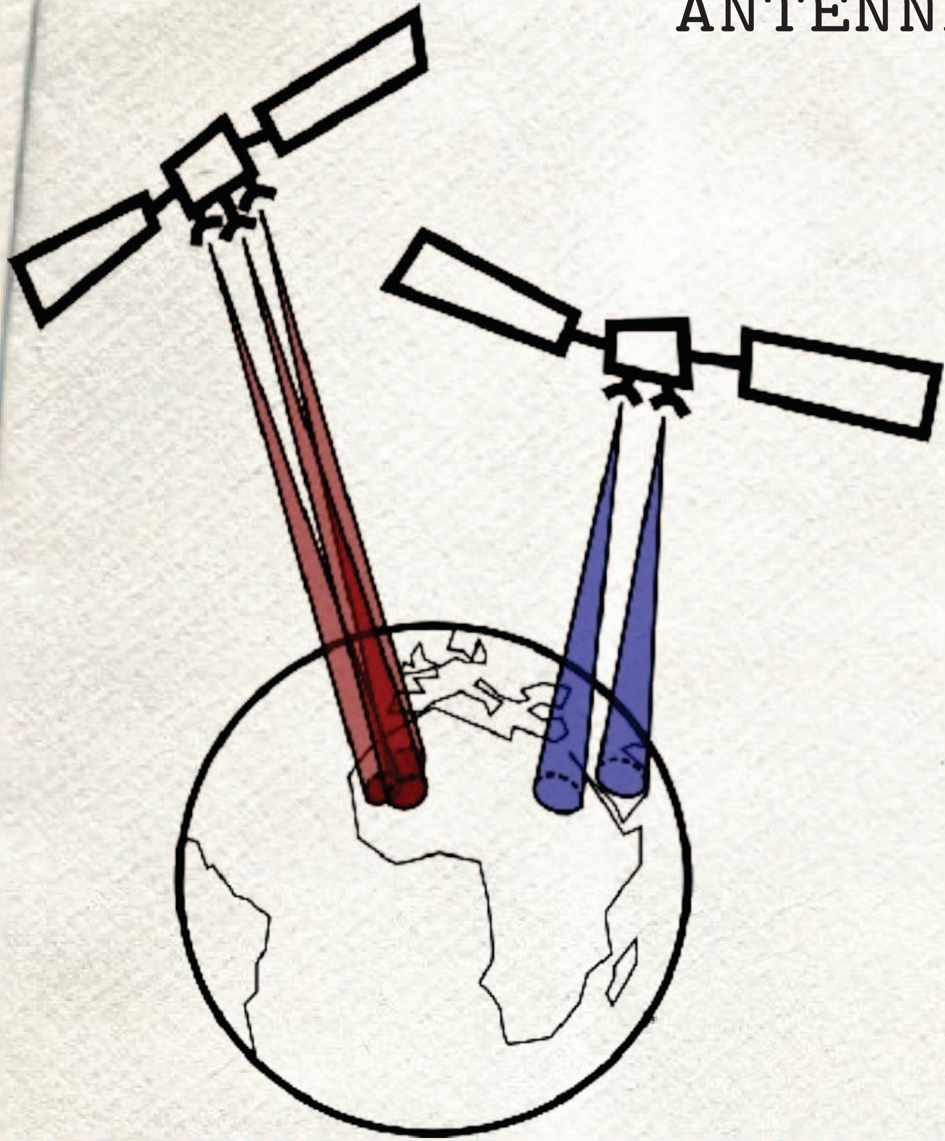
- HORN ANTENNAS
  - AS FEEDS FOR REFLECTOR TYPE ANTENNAS ON E/S
  - WIDE BEAM COVERAGE FOR SATELLITES

- REFLECTOR ANTENNAS
  - REFLECTIVE SURFACE ILLUMINATED BY FEED HORN

ANTENNAS IV

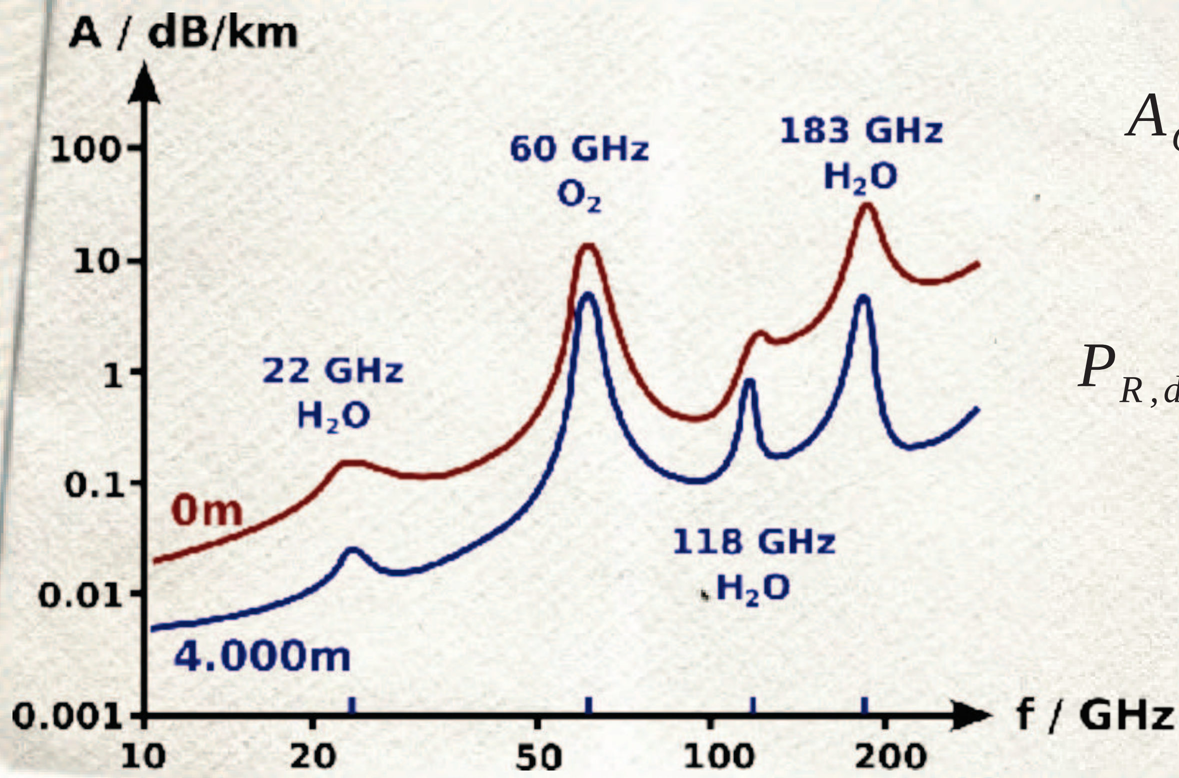


- SEPARATE ANTENNAS
  → SPOT BEAMS
- MULTIPLE FEEDS
- ARRAY ANTENNA
  → PHASED ARRAY ANTENNAS

  → MULTIPLE BEAMS & BEAMSHAPING

CHANNEL CHARACTERISTICS I

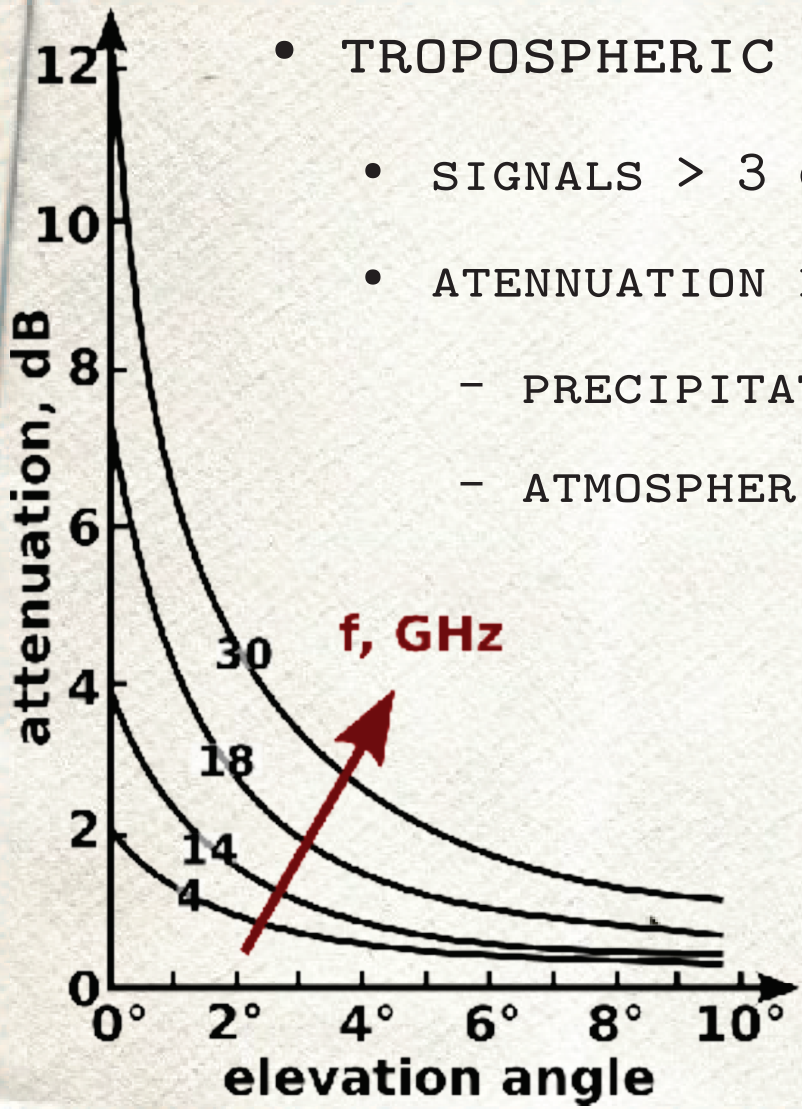
- AWGN – ADDITION OF WHITE GAUSSIAN NOISE
- ATTENUATION DUE TO OXYGEN AND WATER VAPOUR



$$A_{O,W} = \int_0^r \left(\gamma_O(r) + \gamma_W(r)\right) dr$$

$$P_{R,dBW} = P_{T,dBW} + G_{R,dB} + G_{T,dB} - L_{FS,dB} - A_{O,W,dB}$$

CHANNEL CHARACTERISTICS II

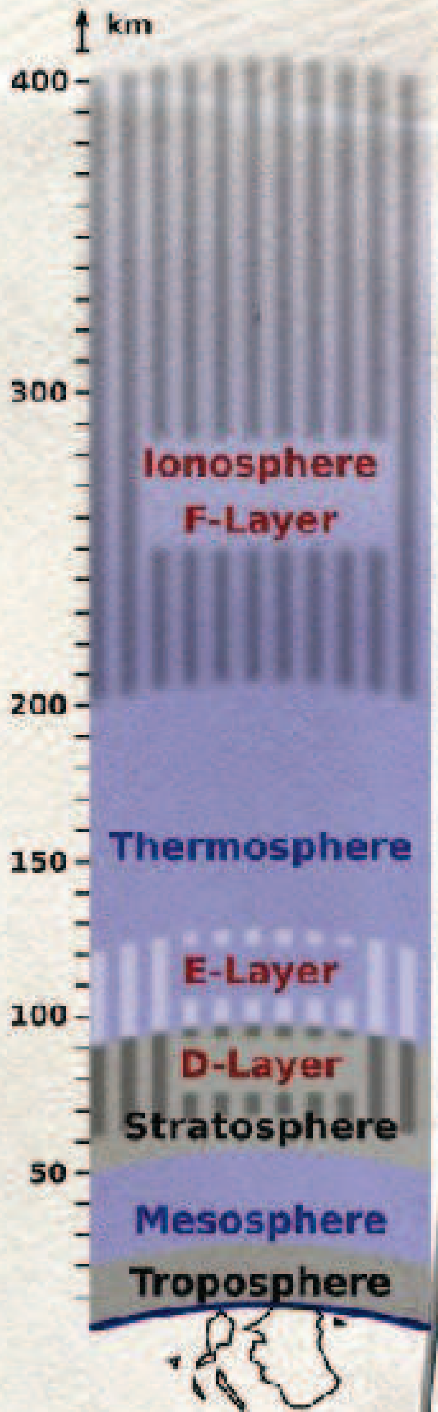


- TROPOSPHERIC EFFECTS
  - SIGNALS > 3 GHZ
  - ATENNUATION DUE TO
    - PRECIPITATION AND CLOUDS
    - ATMOSPHERIC ABSORPTION

- DEPOLARISATION
- REFRACTION & SCINTILLATION
- SHADOWING & MULTIPATH EFFECTS

CHANNEL CHARACTERISTICS III

- IONOSPHERE
  - IONIZED BY SOLAR RADIATION
  - MONITORING
    TEC – TOTAL ELECTRON CONTENT
  - D-LAYER
    ABSORPTION OF HF-RADIO WAVES < 10 MHZ
  - E-LAYER
    HAS LITTLE EFFECT
  - F-LAYER
    RESPONSIBLE FOR MOST RF PROPAGATION OF RADIO WAVES

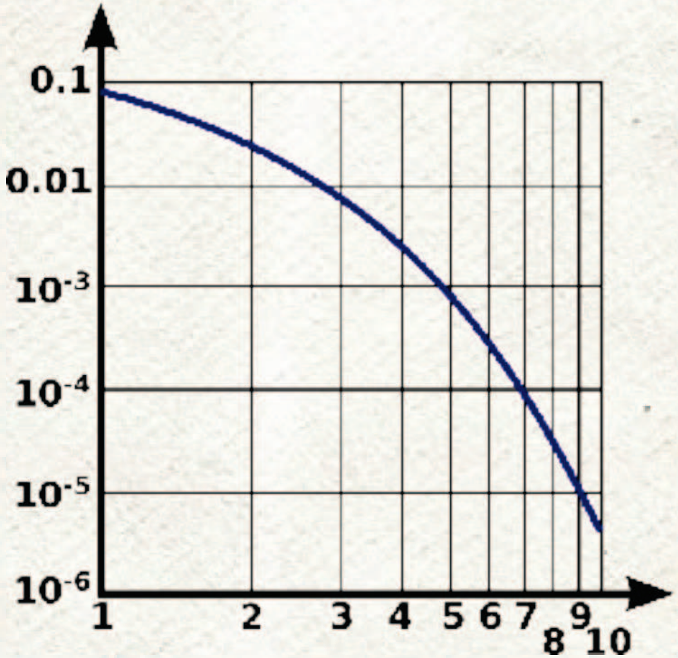


NOISE I

- DIGITAL LINKS: BIT ERROR RATE

$$BER = \frac{1}{2} erfc \sqrt{\frac{E_b}{N_0}}$$

$$BER\left(\frac{E_b}{N_0}\right)$$



$$\frac{E_b}{N_0}$$

BIT ENERGY

$$E_b = \frac{P_{avg}}{R_b}$$

NOISE DENSITY

$$N_0 = \frac{P_N}{B_N} = k \cdot T$$

- ANALOG LINKS: CARRIER-TO-NOISE-RATIO

$$\frac{C}{N0} = \frac{E_b \cdot R_b}{N_0}$$

NOISE II

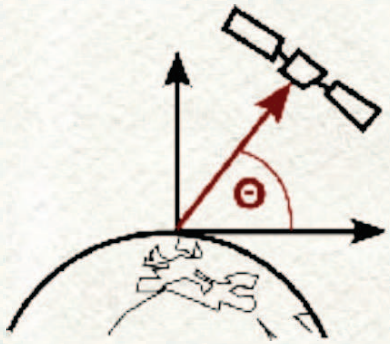
- THERMAL NOISE POWER $P = k_B B T$
- ANTENNA NOISE TEMPERATURE

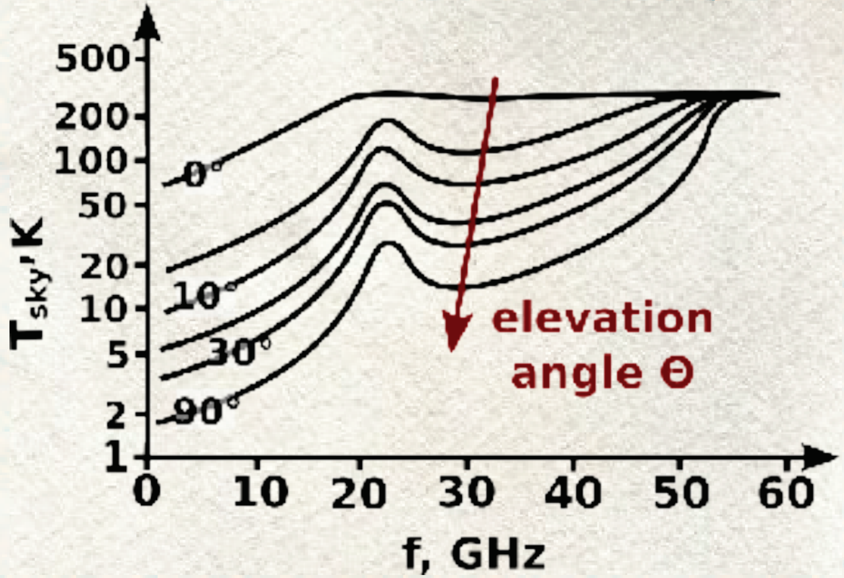
$$T_A = \frac{1}{4\pi} \int_0^{2\pi} \int_0^{2\pi} T_b(\theta,\phi) G(\theta,\phi) \sin\theta \, d\theta \, d\phi$$

- SATELLITE RECEIVING ANTENNA
  - AMOUNT OF NOISE CAPTURED IS SUM OF NOISE FROM EARTH AND OUTER SPACE
  - T_A DEPENDS ON FREQUENCY, ORBITAL POSITION & COVERAGE AREA
  - → SYSTEM NOISE TEMPERATURE $T_{sys,sat} \approx T_0 + T_{LNA}$

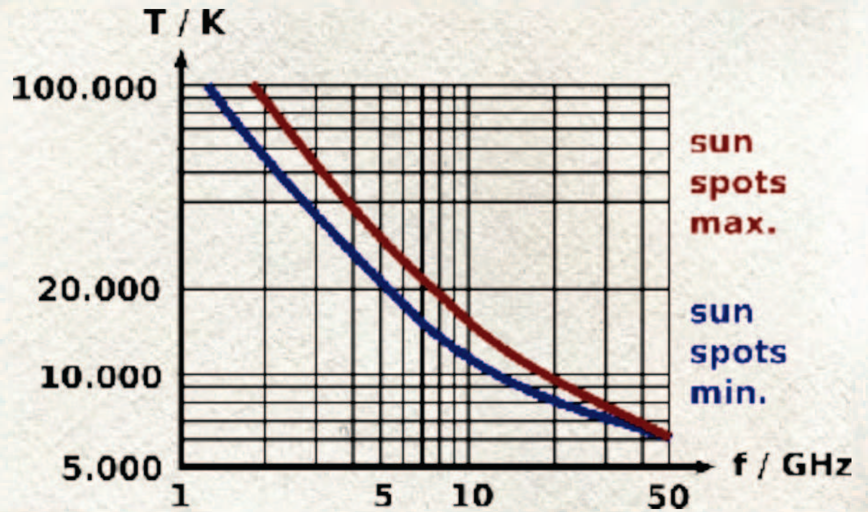
NOISE III

- E/S RECEIVING ANTENNA
  - BRIGHTNESS TEMPERATURE OF THE SKY





  - NOISE CONTRIBUTIONS FROM SUN & MOON
  - COSMIC NOISE



NOISE IV

- E/S RECEIVING ANTENNA
  - CLEAR SKY CONDITIONS:

$$T_{A,clear} = T_{sky} + T_{ground}$$

  - RAIN: $$T_{A,rain} = \frac{T_{sky}}{A_{rain}} + T_{ground} + T_{rain}\left(1 - \frac{1}{A_{rain}}\right)$$

$$T_{A,clear} < T_{A,rain}$$

  - → SYSTEM NOISE TEMPERATURE

$$T_{sys,E/S} \approx \frac{T_A}{L_{F,r}} + T_0\left(1 - \frac{1}{L_{F,r}}\right) + T_{LNA}$$

DOPPLER EFFECTS

- SATELLITE MOVES RELATIVE TO FIXED POSITION ON EARTH
  → DOPPLER EFFECTS

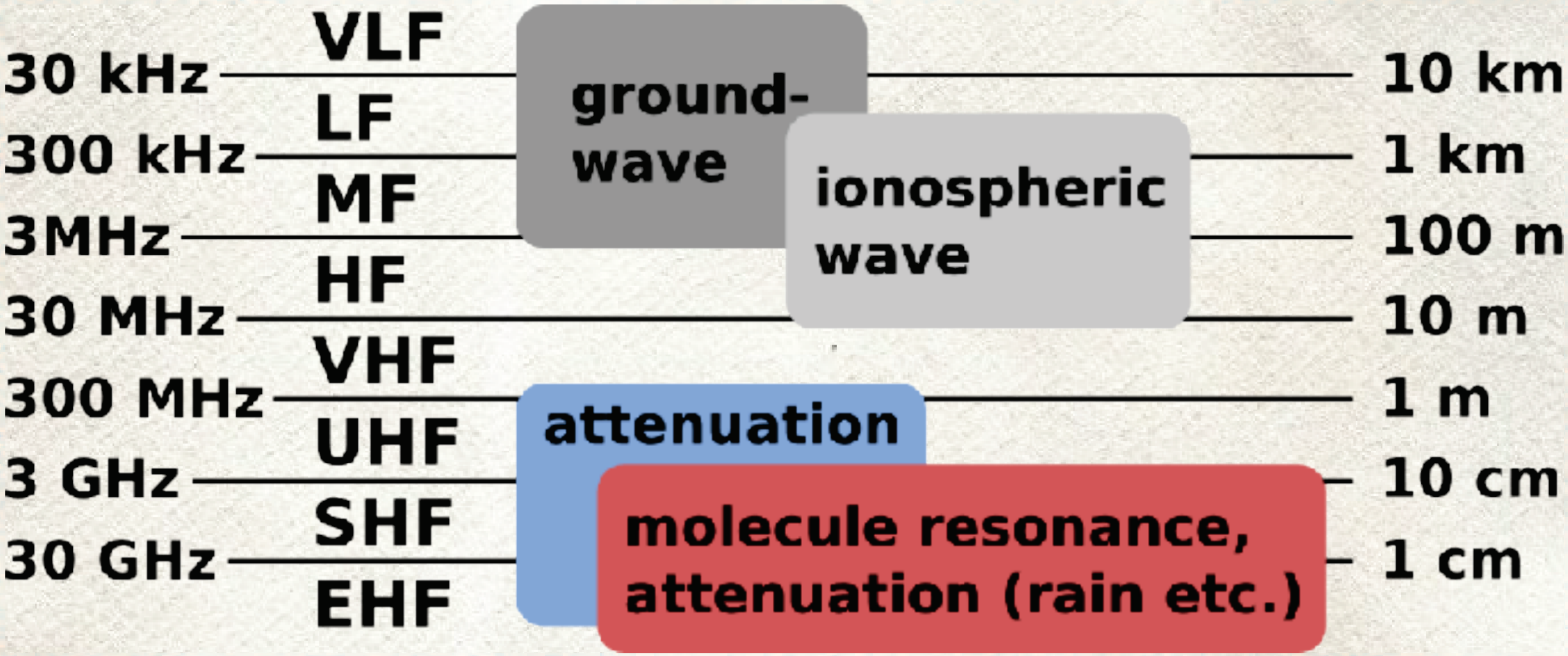
- DOPPLER FREQUENCY

$$\Delta f_d = f_c \frac{v_r}{c}$$

WITH THE RELATIVE RADIAL VELOCITY

$$v_r = \frac{dR}{dt}$$

FREQUENCY BANDS I



SO – WHY HIGH FREQUENCIES?

FREQUENCY BANDS II

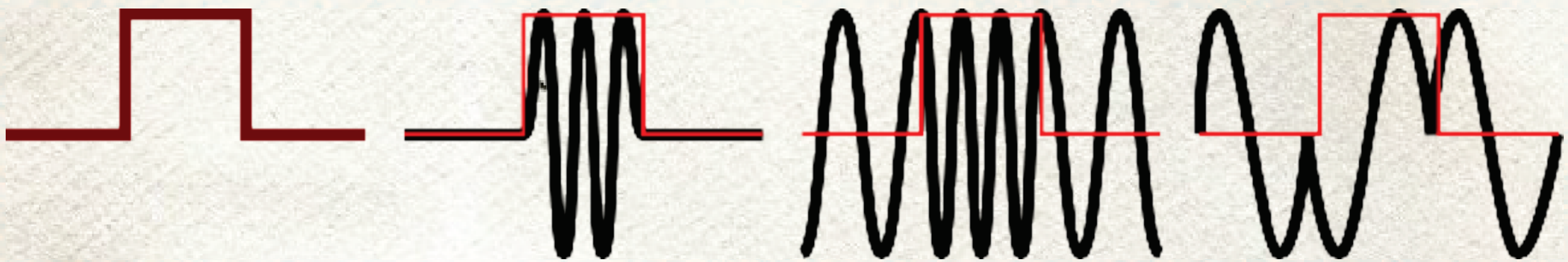
- SATELLITE COMMUNICATION BANDS

BAND NAME	SYMBOL (FREQUENCY)	UL	DL
UHF	L BAND (1-2 GHZ)	1,6 GHZ	1,5 GHZ
SHF	C BAND (4-8 GHZ)	5,925-6,425 GHZ	3,7-4,2 GHZ
	X BAND (8-12 GHZ)	7,9-8,4 GHZ	7,25-7,75 GHZ
	KU BAND (12-18 GHZ)	14-14,5 GHZ 11,45-11,7 GHZ 11,7-12,2 GHZ	10,95-11,2

- FREQUENCY ALLOCATIONS DEPEND ON
  - REGION
  - SERVICE (FSS, MSS, MMSS, ISS...)

MODULATION I

- CARRIER + INFORMATION → SIGNAL
- ANALOG VS. DIGITAL
- BASIC CONCEPTS OF MODULATION
  - ASK – AMPLITUDE-SHIFT KEYING
  - FSK – FREQUENCY-SHIFT KEYING
  - PSK – PHASE-SHIFT KEYING



MODULATION II

- BINARY PHASE-SHIFT KEYING
  - 1 BIT PER SYMBOL

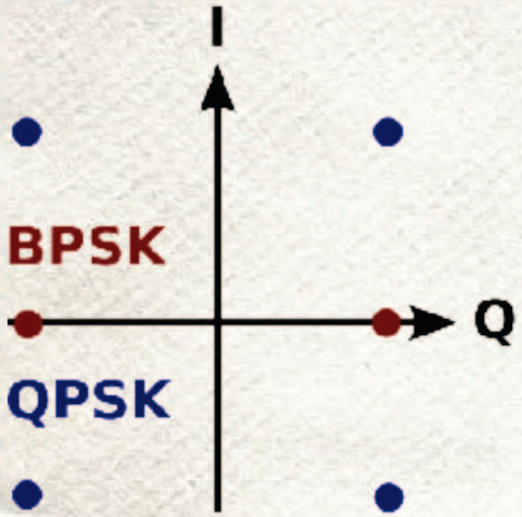
    $$s \in \{+1, -1\}$$

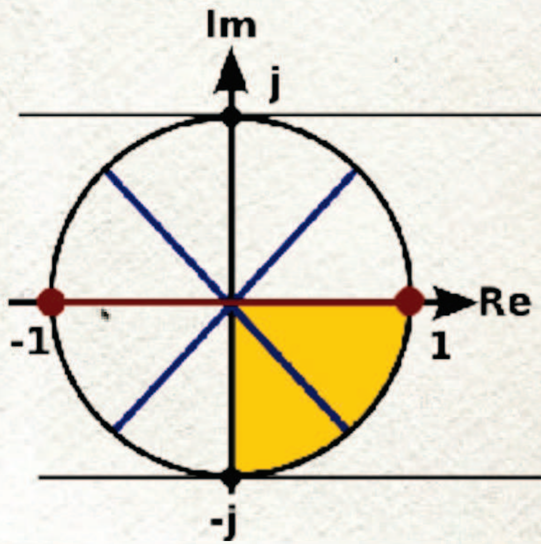
SYMBOL	BIT	I	Q
s1	0	1	0
s2	1	-1	0

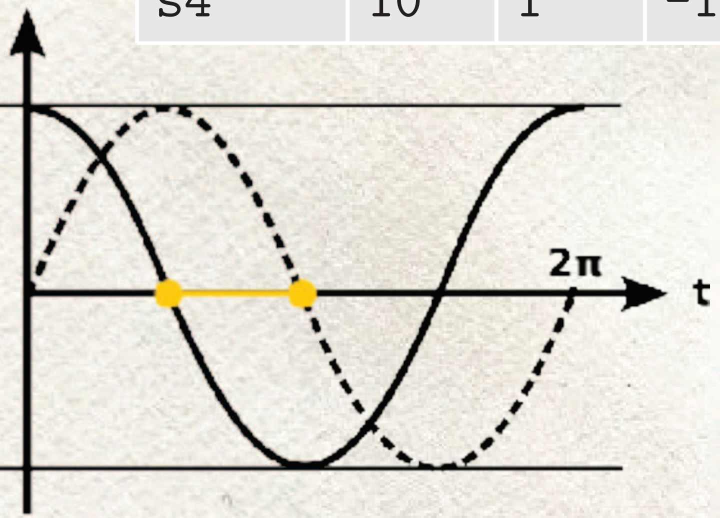
- QUADRATURE PHASE-SHIFT KEYING
  - 2 BITS PER SYMBOL

    $$s \in \{1+j, 1-j, -1+j, -1-j\}$$

SYMBOL	BIT	I	Q
s1	00	1	1
s2	01	-1	1
s3	11	-1	-1
s4	10	1	-1

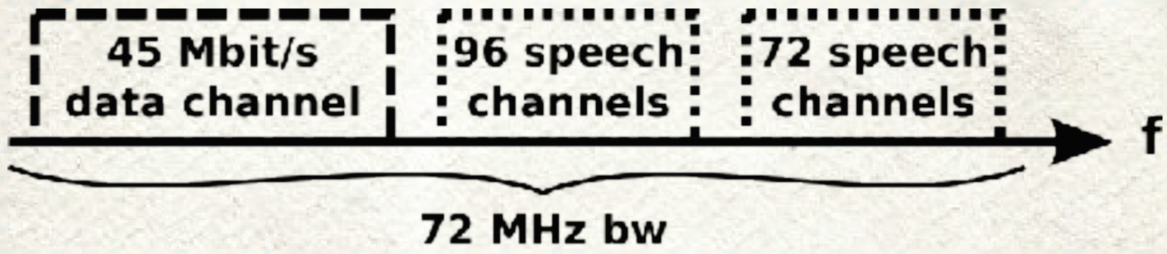






MULTIPLE ACCESS I

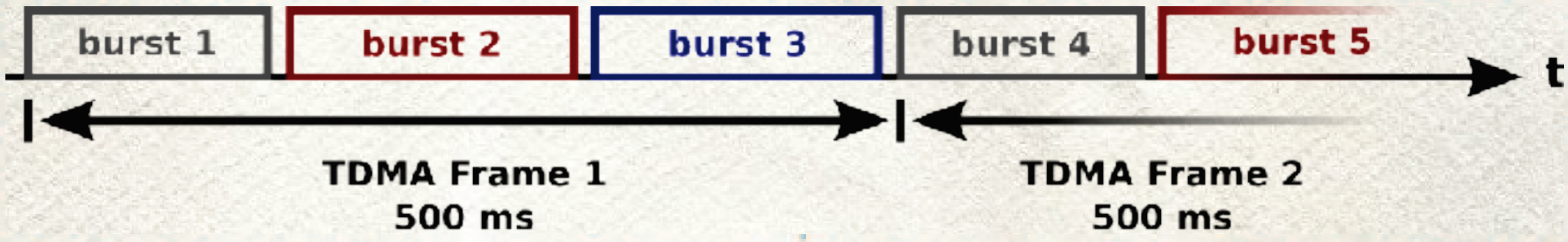
- FDMA – FREQUENCY-DIVISION MULTIPLE ACCESS



  - TRANSPONDER BANDWIDTH MUST BE PREASSIGNED BY FREQUENCY DIVISION
  - + SIMPLE, WELL PROVEN
  - – INTERMODULATION PRODUCTS

MULTIPLE ACCESS II

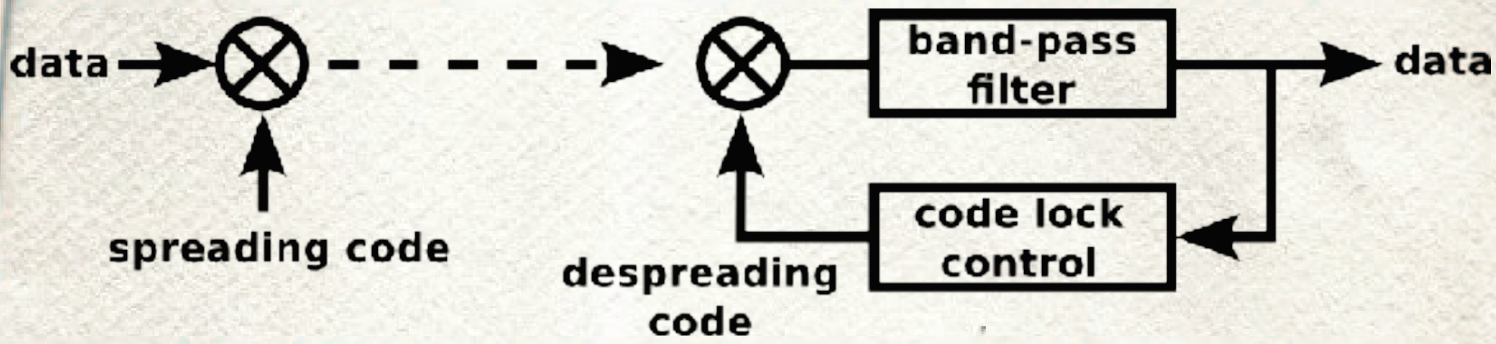
- TDMA – TIME-DIVISION MULTIPLE ACCESS



  - BURST TIME PLAN: TRANSMISSION WITHIN DIFFERENT TIME SLOTS
  - + HIGH THROUGHPUT FOR MANY SUBSCRIBER STATIONS
  - – SYNCHRONIZATION REQUIRED
    INTERSYMBOL INTERFERENCE

MULTIPLE ACCESS III

- DIRECT SEQUENCE SPREAD SPECTRUM

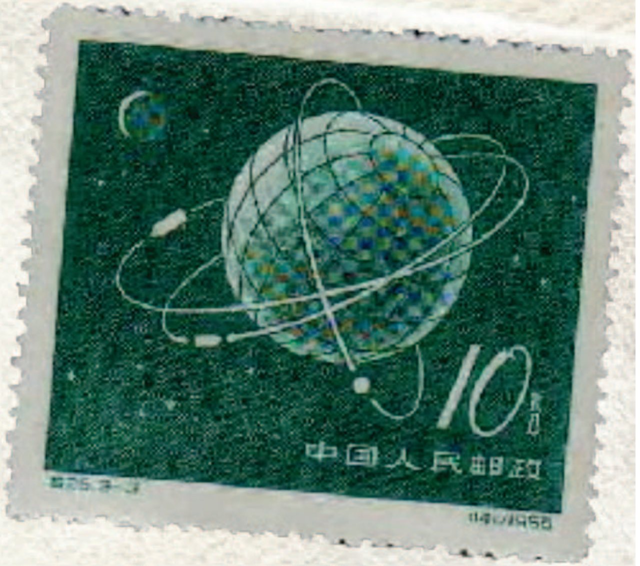


  - UNCORELLATED SIGNALS AND INTERFERENCES LARGELY REJECTED ACCORDING TO PROCESSING GAIN

$$G_{processing} = \frac{bw_{spread}}{bw_{data}}$$

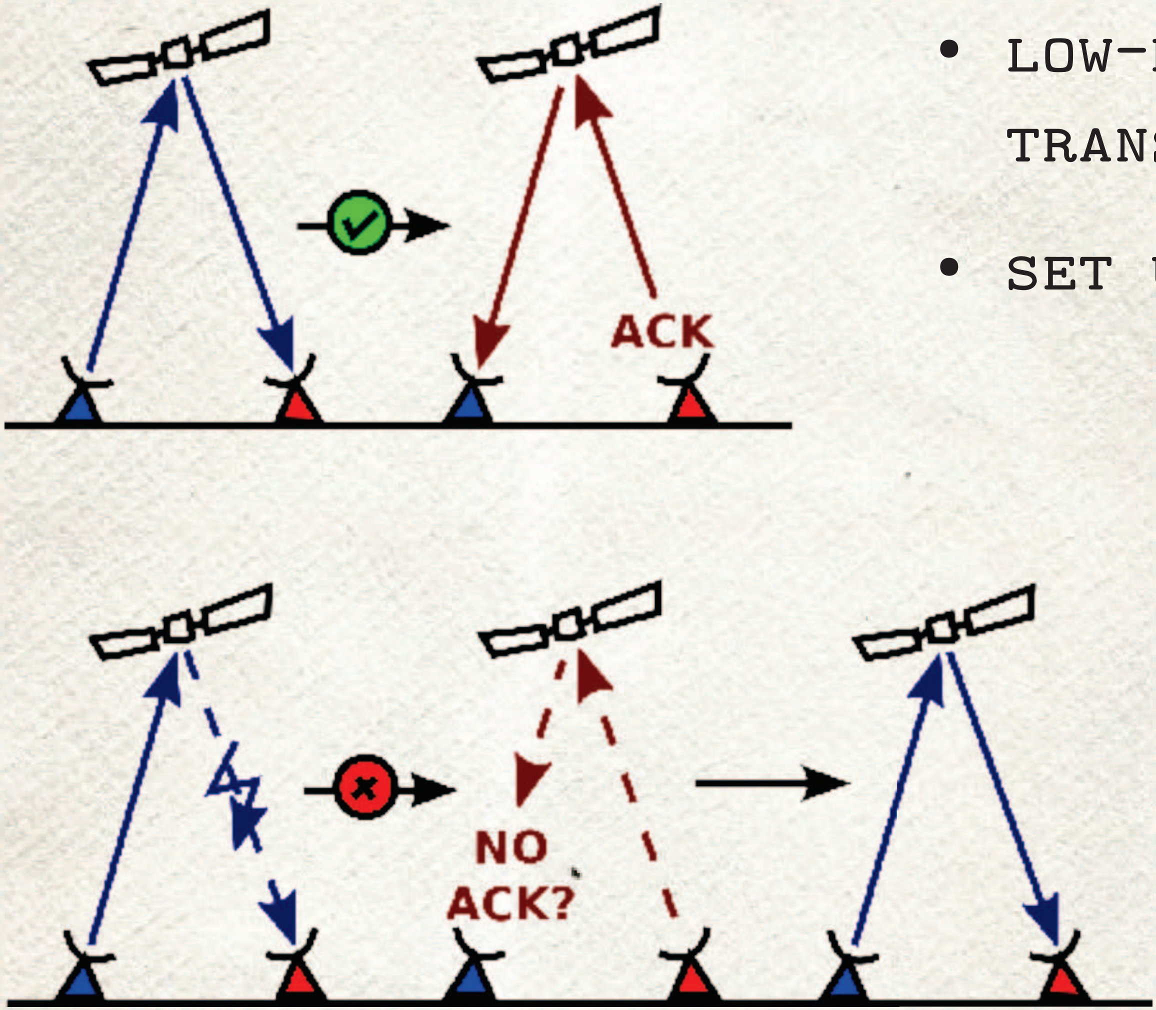
  - SMALL EFFECT ON OTHER TRANSMISSIONS IN SHARED FREQUENCY BANDS

MULTIPLE ACCESS IV



- CDMA –
  CODE-DIVISION MULTIPLE ACCESS
  - MULTIPLE-ACCESS TECHNIQUE BASED ON SPREAD SPECTRUM
  - ALL SIGNALS TRANSMITTED WITHIN COMMON BANDWIDTH
  - \+ NO SYNCHRONIZATION
    NO INTERFERENCES
    SMALL INTERFERENCES PRODUCED
  - \- SMALL DATA THROUGHPUT
    COMPLEX

RANDOM ACCESS PROTOCOL – ALOHA



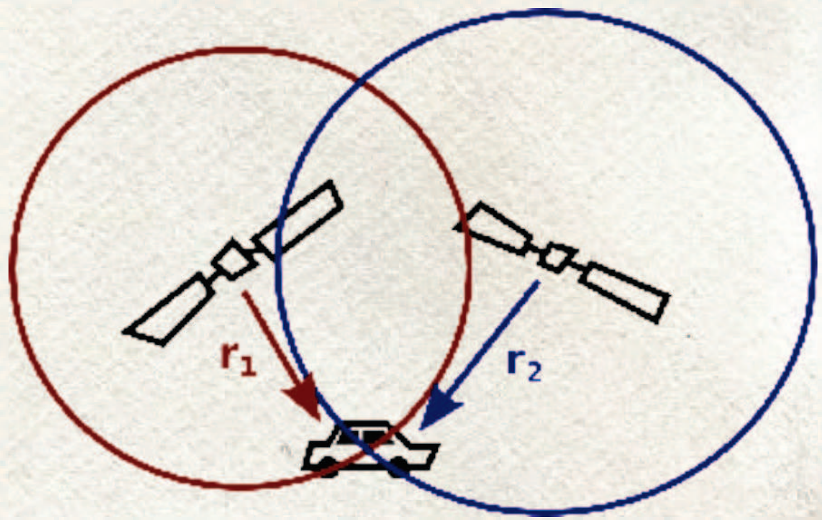
- LOW-DATA RATE, BURSTY TRANSMISSIONS
- SET UP CONNECTIONS

    - PURE ALOHA
    - SELECTIVE REJECT ALOHA
    - SLOTTED ALOHA
    - ...

SATELLITE NAVIGATION I

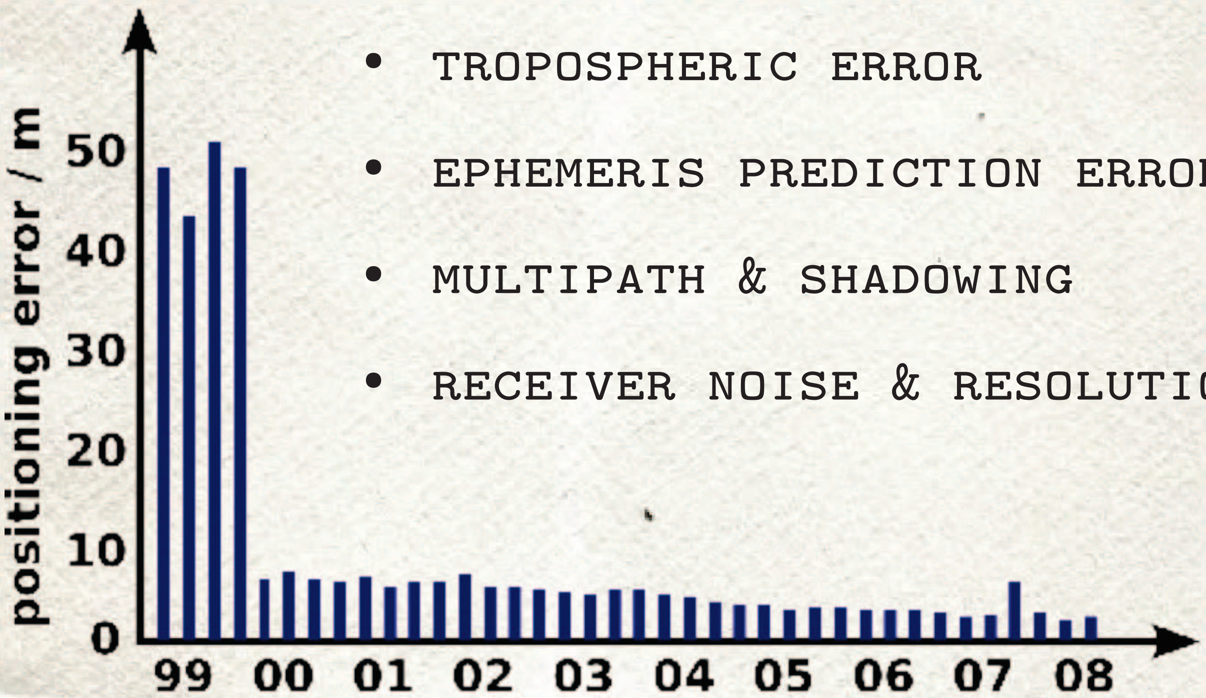
- TOA – TIME OF ARRIVAL
  - MEASURING SIGNAL PROPAGATION TIME Δt
    → CALCULATING DISTANCE TO EMITTER $r = c \cdot \Delta t$
  - OFFSET OF RECEIVER CLOCK Δt_r
    → <u>FOUR</u> EMITTER SIGNALS NEEDED $r_i = c(\Delta t_i - \Delta t_r)$

$$r_1 = \sqrt{(x_{s1}-x_r)^2+(y_{s1}-y_r)^2+(z_{s1}.zr)^2}+c\Delta t_r$$
$$r_2 = \sqrt{(x_{s2}-x_r)^2+(y_{s2}-y_r)^2+(z_{s2}.zr)^2}+c\Delta t_r$$
$$r_3 = \sqrt{(x_{s3}-x_r)^2+(y_{s3}-y_r)^2+(z_{s3}.zr)^2}+c\Delta t_r$$
$$r_4 = \sqrt{(x_{s4}-x_r)^2+(y_{s4}-y_r)^2+(z_{s4}.zr)^2}+c\Delta t_r$$



SATELLITE NAVIGATION II

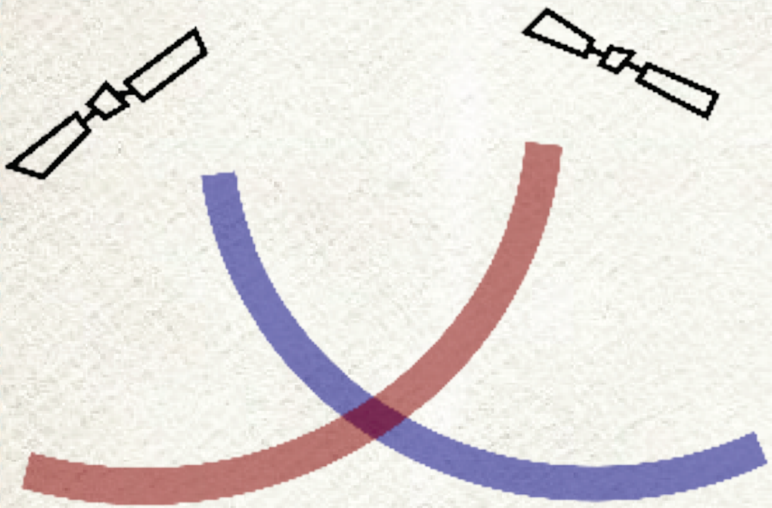
- ERROR SOURCES
  - SATELLITE CLOCK ERRORS
  - IONOSPHERIC ERROR → 2^{ND} FREQUENCY
    GPS: L1 = 1575.42 MHZ   L2 = 1227.60 MHZ
  - TROPOSPHERIC ERROR
  - EPHEMERIS PREDICTION ERRORS
  - MULTIPATH & SHADOWING
  - RECEIVER NOISE & RESOLUTION



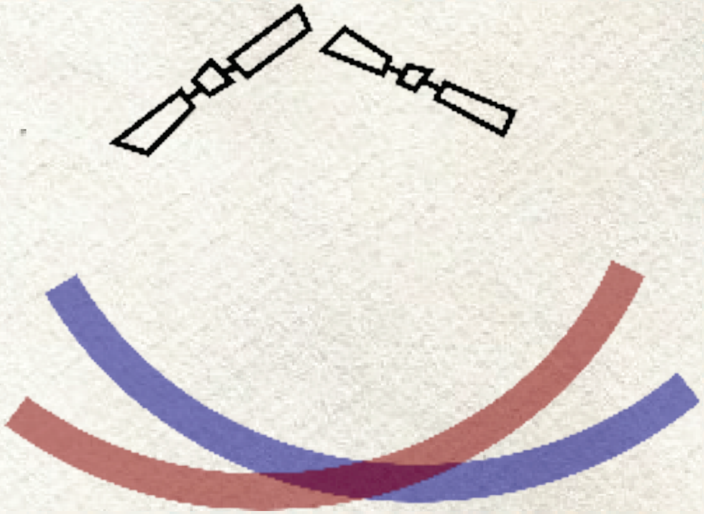
GPS

SATELLITE NAVIGATION III

- DOP – DILUTION OF PRECISION
  - POSITIONING ERROR ALSO DEPENDS ON THE POSITION OF THE SATELLITES



GOOD DOP VALUE



BAD DOP VALUE

SATELLITE NAVIGATION IV

- GPS: NAVIGATION MESSAGE EXAMPLE

Ephemeris Data Set Used in Pseudo-Range Navigation Example (GPS Time = 150000 seconds)

Ephemeris Data Parameter	Value	Value	Value	Value
SV	15	27	31	7
Issue of Data Ephemeris	196	200	125	125
Cosine Correction to Inclination	-9.313225746E-08	1.136213541E-07	2.793967724E-08	-1.285225153E-07
Sine Correction to Inclination	-3.725290298E-09	-1.061707735E-07	9.126961231E-08	-1.322478056E-07
Cosine Correction to Radius	146.09375	148.84375	306.28125	322
Sine Correction to Radius	-69.9375	79.09375	-130.71875	-128.5
Cosine Correction to Latitude	-3.630295396E-06	4.122033715E-06	-6.921589375E-06	-6.720423698E-06
Sine Correction to Latitude	1.228414476E-05	1.15185976E-05	3.74391675E-06	2.983957529E-06
Mean Motion Difference	4.023024718E-09	4.513045129E-09	4.656622538E-09	4.650550857E-09
Eccentricity	0.006778693292	0.01127019501	0.005836840719	0.006999379606
Rate of Inclination Angle	1.817932867E-10	-5.928818388E-11	-5.418082828E-10	-4.207318109E-10
Orbital Inclination	0.9721164968	0.9459886628	0.9633626261	0.963950905
Mean Anomaly at Reference Time	-0.8856059028	0.1225249	-0.6775731485	3.019737078
Argument of Perigee	1.738558535	2.601538834	0.6715504011	-2.568758665
Rate of Right Ascension	-7.783538501E-09	-8.143553497E-09	-8.411421798E-09	-8.25355808E-09
Longitude of Ascending Node	-2.8654714	0.2200327977	2.320031302	2.317137898
Square Root of Semi-Major Axis	5153.618444	5153.653282	5153.789852	5153.644896
Reference Time Ephemeris	151200	151200	136800	151200

source: www.colorado.edu/geography/gcraft/notes/gps/gps_f.html

SATELLITE NAVIGATION V

- ONE LAST THING – RELATIVISTIC EFFECTS
  - SPECIAL RELATIVITY: OBSERVER ON THE GROUND SHOULD OBSERVE ON-BOARD CLOCK TICK MORE SLOWLY

$$\Delta t \approx 7\,\mu s/day$$

  - GENERAL RELATIVITY: EARTH'S MASS BENDS SPACETIME → CLOCKS FURTHER AWAY FROM EARTH TICK FASTER

$$\Delta t \approx 45\,\mu s/day$$

  - → ERROR OF $\Delta t \approx 45-7 = 38\,\mu s/day$

AWSUM THX!

i.meister@ieee.org

FURTHER READING:

- EVANS: *SATELLITE COMMUNICATIONS SYSTEMS*
- *MESSERSCHMID, FASOULAS: RAUMFAHRTSYSTEME*
- SALZBURGER: *SIGNALVERARBEITUNG UND MESSDATENERFASSUNG*
- CORAZZA: *DIGITAL SATELLITE COMMUNICATIONS*
- *WWW.COMPLEXTOREAL.COM/TUTORIAL.HTM*