Slides From ATI Professional Development Short Course

Advanced Satellite Communications System

Instructor:

Dr. John Roach

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Outline of Topics

I. OVERVIEW OF SATELLITE COMMUNICATIONS; HISTORY

II. SATELLITE ORBITS

III. COMM SATELLITE CHARACTERISTICS; TRANSPONDERS; TRANSPONDER USAGE TYPES: CONNECTIVITY; MULTIPLE ACCESS METHODS

IV. COMMUNICATIONS LINK ANALYSIS
- DEFINITIONS OF EIRP, G/T, Eb/No, Es/No
- LINK BUDGET EQUATIONS; EXAMPLE LINK BUDGET
- DEFINITIONS OF NOISE TEMPERATURE, NOISE FACTOR
- ATMOSPHERIC LOSSES, INCLUDING RAIN

V. COMMON MODULATION TECHNIQUES
- BPSK, QPSK, OFFSET QPSK (OQPSK)
- STANDARD PULSE FORMATS, FREQUENCY SPECTRA
- PSK RECEIVER DESIGN TECHNIQUES; CARRIER RECOVERY; TIMING RECOVERY

VI. OVERVIEW OF ERROR HANDLING AND ERROR CODES;
- STANDARD CODES; CODING PERFORMANCE AND CODING GAIN;

VII. OVERVIEW OF SCRAMBLING & ENCRYPTION TECHNIQUES;
- EFFECT ON CHANNEL PERFORMANCE

Outline of Topics

VIII. EARTH STATION RF EQUIPMENT
- HPAs, LNAs, FREQUENCY CONVERTERS
- GAIN AND PHASE DISTORTION
- HPA AM/AM, AM/PM
- INTERMODULATION PRODUCTS
- FREQUENCY CONVERTERS; OSCILLATOR OR PHASE NOISE
- COMMUNICATIONS MODELING

IX. TDMA NETWORKS; TIME SLOTS; PREAMBLE; EXAMPLE NETWORK

X. TRANSMISSION OF TCP/IP OVER SATELLITE; USE OF PEP

XI. DVB APPROACH TO SMALL APERTURE TERMINALS; DVB-S; DVB-RCS

XII. EARTH TERMINAL ANTENNAS; POINTING, TRACKING; REGULATORY REQUIREMENTS

XIII. SPREAD SPECTRUM TECHNIQUES; DIRECT SEQUENCE; FREQUENCY HOP; SHORT, LONG CODES; LONG CODE ACQUISITION, TRACKING

XIV. NYQUIST SIGNALING; BANDWIDTH EFFICIENT MODULATION (BEM) TYPES

XV. CONVOLUTIONAL CODING AND VITERBI DECODING

XVI. EMERGING DEVELOPMENTS AND FUTURE TRENDS

ACRONYMS

ACI	Adjacent Channel Interference
ACK	Acknowledgement
ACS	Add-Compare-Select
AES	Advanced Encryption System
AFC	Automatic Frequency Control
AGC	Automatic Gain Control
AJ	Anti-Jam
ALC	Automatic Level Control
AM	Amplitude Modulation
AM/AM	Ratio of AM on Output to AM on Input of an RF Device
AM/PM	Ratio of PM on Output to AM on Input of an RF Device
ANIK	Series of Canadian Communications Satellites
ASI	Adjacent Satellite Interference
ASK	Amplitude Shift Keying
APK	Amplitude Phase Shift Keying
ARIANE	A French Heavy Lift Launch Vehicle
ARQ	Automatic Repeat Request
AWGN	Additive White Gaussian Noise
BB	Baseband
BCH	Bose Chauhuri Hocquenheim (Block Code)
BDC	Block (Frequency) Downconverter
BER	Bit Error Rate
BFSK	Binary Frequency Shift Keying

ACRONYMS

BLOS	Beyond Line-of-Sight
BoD	Bandwidth on Demand
BOL	Beginning of Life
BPF	Bandpass Filter
BPS	Bits per Second
BPSK	Binary Phase Shift Keying
BSC	Binary Symmetric Channel
BUC	Block (Frequency) Upconverter
BW	Bandwidth
C Band	Frequency Band from 4 GHz to 6 GHz
CBR	Carrier-Bit Recovery (Intelsat TDMA Header Segment)
CCIR	Comite Consultatif International des Radiocommunications (now replaced by ITU-R)
CCITT	Comite Consultatif International Telegraphique et Telephonique (now replaced by ITU-T)
CDC	Control and Delay Channel (Intelsat TDMA Header Segment)
CDMA	Code Division Multiple Access
CEPT	Conference Eurpeene des Postes
CEVD	Convolutionally Encoded-Viterbi Decoded
C/I	Carrier to Interference Ratio
C/IM	Carrier to Intermodulation Product Ratio
C/kT	Carrier to Noise Density Ratio
CMA	Control, Monitor, and Alarm

ACRONYMS

C/N	Carrier to Noise Ratio
C/No	Carrier to Noise Density Ratio
CNR	Carrier to Noise Ratio
CODEC	Coder/Decoder
COMSAT	Communication Satellite Corporation
COTM	Communications-on-the-Move
CPE	Customer Premises Equipment
CPFSK	Continuous Phase Frequency Shift Keying
CPSK	Coherent Phase Shift Keying
CSC	Control and Signaling Channel
CVSD	Continuously Variable Slope Delta Modulation
DA	Demand Assignment
DAMA	Demand Assignment Multiple Access
dB	Decibel
dBi	Decibel with respect to Isotropic
dBm	Decibel with respect to 1 Milliwatt
DBS	Direct Broadcast Satellite
dBW	Decibel with respect to 1 Watt
D/C	Frequency Downconverter
DEMOD	Demodulator
DEMUX	Demultiplexer
DE	Differentially-Encoded,
DES	Data Encryption Standard
DL	Downlink
DM	Delay Modulation
DMC	Discrete Memoryless Channel

ACRONYMS

DC	(Frequency) Down Converter
DS	Direct Sequence (CDMA spreading technique)
DPSK	Differential Phase Shift Keying
DQPSK	Differential Quadrature Phase Shift Keying
DSB-SC	Double Sideband-Suppressed Carrier
DSCS	Defense Satellite Communication System
DSI	Digital Speech Interpolation (Intelsat terminology)
DVB-RCS	DVB-Return Channel by Satellite
DVB-S	Digital Video Broadcasting-Satellite
DVB-S2	Digital Video Broadcasting-Satellite, Generation 2
Eb/No	Energy per Bit to Noise Density Ratio
ECC	Error Correction Coding
EDAC	Error Detection and Correction
EHF	Extra High Frequency
EIRP	Effective Isotropically Radiated Power
EOL	End of Life
EMP	Electromagnetic Pulse
ES	Earth Station
ESA	European Space Agency
Es/No	Energy per Symbol to Noise Density Ratio
ET	Earth Terminal
FCC	U.S. Federal Communications Commission
FDM	Frequency Division Multiplex
FDMA	Frequency Division Multiple Access

ACRONYMS

FEC	**Forward Error Correction**
FET	**Field Effect Transistor**
FFH	**Fast Frequency Hop**
FFSK	**Fast Frequency Shift Keying**
FH	**Frequency Hop**
FL	**Forward Link (VSAT or DVB terminology)**
FOM	**Figure of Merit**
FM	**Frequency Modulation**
FSK	**Frequency Shift Keying**
GEO	**Geosynchronous Earth Orbit**
GHz	**Gigahertz**
G/T	**Ratio of Antenna Receive Gain to Noise Temperature**
HEO	**Highly Elliptical Orbit**
HF	**High Frequency (3-30 MHz)**
HP	**Horizontal Polarization**
HPA	**High Power Amplifier**
HPF	**High Pass Filter**
Hz	**Hertz**
IBO	**Input Backoff**
IC	**Integration Contractor**
IF	**Intermediate Frequency**

ACRONYMS

IFL	Interfacility Link
INMARSAT	International Maritime Satellite Organization
INTELSAT	International Telecommunications Satellite Organization
IOT	In-Orbit Test
IP	Internet Protocol
IPA	Intermediate Power Amplifier
ISL	Inter-Satellite Link
ITU	International Telecommunications Union
K	Kelvin, unit of temperature with respect to –273^0C
K-Band	10-30 GHz
Ka-Band	15-30 GHz
KBPS or Kb/s	Kilobits per Second
KHz	Kilohertz
KPA	Klystron Power Amplifier
Ku-Band	10-15 GHz
KW	Kilowatts
L-band	1-2 GHz
LEO	Low Earth Orbit
LHCP	Left Hand Circular Polarization
LNA	Low Noise Amplifier
LO	Local Oscillator
LOS	Line-of-Sight
LPD	Low Probability of Detection
LPF	Low Pass Filter
LPI	Low Probability of Intercept

ACRONYMS

LSB	Least Significant Bit
M&C	Monitor and Control
MA	Multiple Access
MAP	Maximum a Posteriori
ML	Maximum Likelihood
MLD	Maximum Likelihood Detector
MLSE	Maximum Likelihood Sequence Estimator
MLSR	Maximum Length Shift Register Sequence
MBPS or Mb/s	Megabits per Second
MCPS or Mc/s	Megachips per Second
MEO	Medium Earth Orbit
MF	Matched Filter
MFSK	M-ary Frequency Shift Keying
MHz	Megahertz
MILSTAR	U.S. Military Satellite System
MODEM	Modulator-Demodulator
MSB	Most Significant Bit
MSK	Minimum Shift Keying
MUX	Multiplexer
mw	Milliwatt
MW	Megawatt
NAK	Negative Acknowledgement
NB	Narrow Band

ACRONYMS

NBW	Noise Bandwidth
NEO	Near Earth Object
NF	Noise Figure
NLOS	Non-Line-of-Sight
NRZ	Non Return to Zero
OBO	Output Backoff
OD	Orbital Debris; Orbit Determination
OQPSK	Offset-QPSK
OMT	Orthomode Transducer
OW	Order Wire
PA	Power Amplifier
PCM	Pulse Code Modulation
P/D	Power Divider
PEP	Performance Enhancing Proxy
PG	Processing Gain
PLL	Phase Lock Loop
PM	Phase Modulation
PN	Pseudo-noise (sequence)
PR	Partial Response Signaling
PRN	Pseudo-random Noise
PSD	Power Spectral Density
PSK	Phase Shift Keying
QAM	Quadrature Amplitude Modulation
QPR	Quadrature Partial Response

ACRONYMS

QPSK	Quadrature Phase Shift Keying
RA	Random Access
RF	Radio Frequency
RHCP	Right Hand Circular Polarization
RL	Return Link (VSAT or DVB terminology)
RMS	Root-Mean-Square
RS	Reed-Solomon Code
RSL	Received Signal Level
RSS	Root Summed Square
Rx	Receiver
RZ	Return to Zero
S-Band	2-4 GHz
S/C	Spacecraft
SC	Service Channel (Intelsat TDMA Header Seqment)
SCPC	Single Channel per Carrier
SFD	Saturation Flux Density
SFH	Slow Frequency Hop
SHF	Super High Frequency
SIT	Satellite Interactive Terminal
SNMP	Simple Network Management Protocol
SNR	Signal to Noise Ratio
SOTM	SATCOM-on-the-Move
SPADE	Intelsat SCPC System
SQPSK	Staggered QPSK

ACRONYMS

SS	Spread Spectrum
SSMA	Spread Spectrum Multiple Access
SSPA	Solid-State Power Amplifier
SW	Switch
TCP	Transmission Control Protocol
TDM	Time Division Multiplexing
TDMA	Time Division Multiple Access
TDRS	Tracking and Data Relay Satellite
TDRSS	NASA Tracking and Data Relay Satellite System
TPC	Turbo Product Code
TT&C	Tracking, Telemetry, and Commanding
TWTA	Traveling Wave Tube Amplifier
Tx	Transmitter
U/C	(Frequency) Upconverter
UDP	User Datagram Protocol
UHF	Ultrahigh Frequency
UL	Uplink
USAT	Ultra Small Aperture Terminal
UW	Unique Word (Intelsat TDMA Header Seqment)
VA	Viterbi Algorithm
VCO	Voltage Controlled Oscillator
VCXO	Voltage Controlled Crystal Oscillator
VP	Vertical Polarization

ACRONYMS

VSAT	**Very Small Aperture Terminal**
W	**Watts**
WB	**Wideband**
WG	**Waveguide**
X-Band	**7-8 GHz**

I. Overview and History

Early History of Satellite Communications

1945 - Arthur C. Clarke wrote about extraterrestrial relays

Passive Reflectors (uplink signals reflected back to earth):

1951 - Bounce off the moon
1960/64 - Bounce off US-launched 100' &135' diameter Echo mylar balloons
1963 - Bounce off Project Westford dipoles in orbit

Active Satellites:

1957 - Russian Sputnik 1- Launch 10/4/1957 – no mission payload

1958 - Explorer I – JPL – measured cosmic rays, etc; Launch: 1/31/1958

1958 - Project Score - US DoD– Launch: 12/18/1958; world's first communications satellite
- **Recorded Christmas message on tape recorder; UHF**
- **First store-&-forward and real time communications**
- **Battery-powered**
- **185 x 1484 km orbit; 32.3° Inclination**

1960 - Courier 1B - US DoD; Launch: 10/4/1960
- **First with solar cells & nickel cadmium batteries**
- **1 Voice channel & TTY, 2 Watts, 1.7 - 1.9 GHz**
- **Orbit altitude: 938 x 1237 km orbit; 28.33° inclination**

Early History of Satellite Communications (cont'd)

1962 **TELSTAR I (AT&T)**
- **First publically available instantaneous repeating satellite**
- **6/4 GHz, 3.3 Watts**
- **First live TV transmission across the Atlantic**
- **600 One-way voice circuits**
- **Demonstrated large earth terminal antennas**

1962 - **Relay (NASA/RCA)**
- **Two 10 Watt transponders (4630 x S.M.; 47.5°)**

1963 - **Syncom II (NASA)**
- **First geosynchronous satellite**
- **Two channels, 500 kHz each**
- **7.31/1.8 GHz, 2 Watts**
- **Inclination: 32° (II) 0.5° (III)**

1965 - **Molniya (USSR)**
- **Elliptical orbit**
- **Inclination angle: 63.4°**

1965 - **Intelsat I (Early bird)**

1966 - **Intelsat II**

1968 - **INTELSAT III**

1969 - **TACSAT I (DOD)**

1971 - **INTELSAT IV**
- **12 36 MHz channels; 6 Watts/channel**

1972 - **ANIK (Canada)**
- **First domestic satellite**

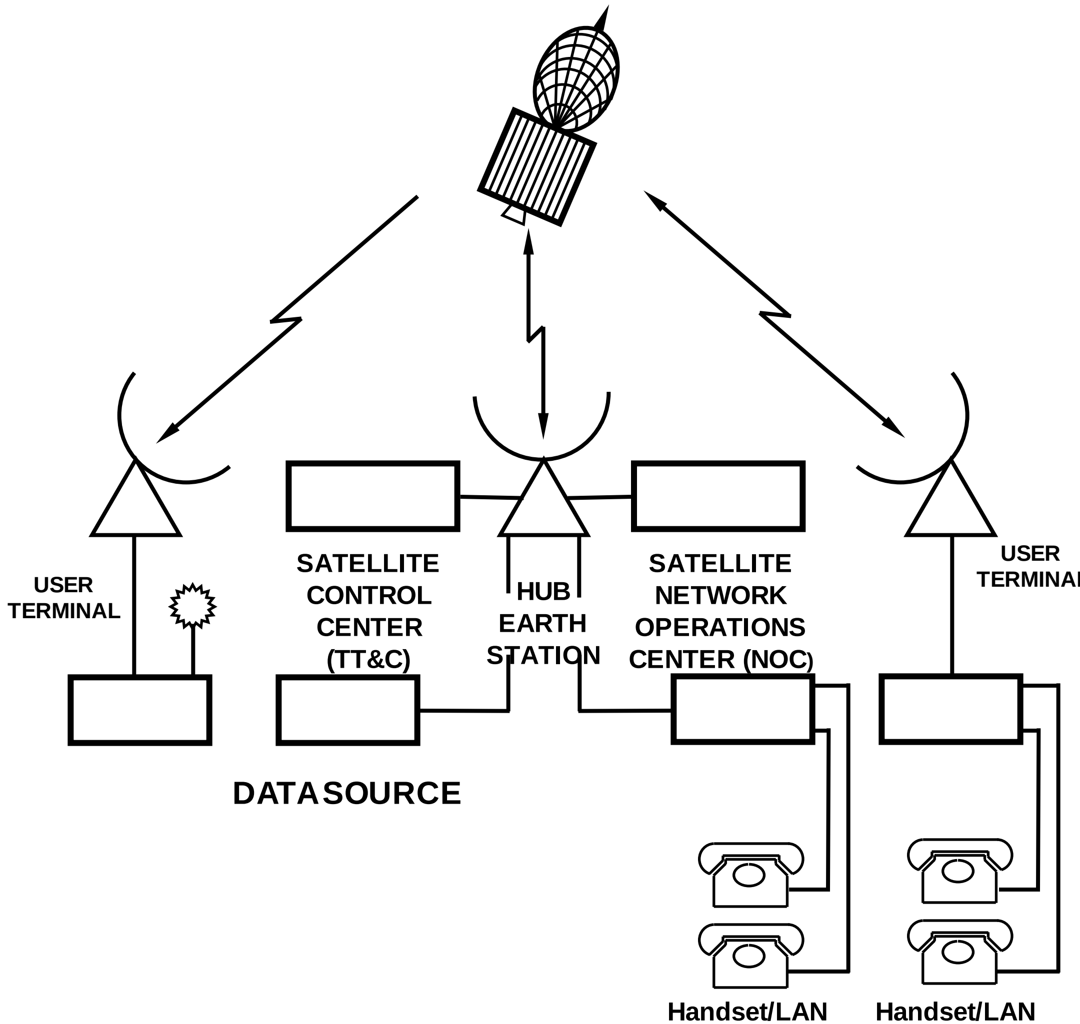
1974 - **WESTAR (Western Union)**
- **First U.S. domestic satellite**

1977 - **Advanced WESTAR/TDRSS**
- **Commercial s/c development with Western Union financing guaranteed by NASA**

1993 - **ACTS (NASA)**
- **First Ka technology satellite**

NASA then turned SATCOM technology development over to industry

General Satellite System Architecture



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Satellite System Operators

- Example Satellite System Operators:
  - SES
  - Intelsat
  - Eutelsat
  - PanAmSat
  - JSAT
  - Telesat Canada
  - Space Communications (Japan)
  - Loral Space and Communications
  - Many other European and Asian operators

- Each analyzes requests for service to assure legal and efficient use
- Each protects their users
  - Operators cooperate to protect each others systems
  - Continuously monitor and control use of their satellites
  - Help investigate/characterize/geolocate interference sources
    - One equipment supplier claims to be capable of locating an interference to within 10 km from GEO

Legal Authorities over Spectrum

- **International Telecommunications Union (ITU):**
  - Controls RF frequency assignments worldwide
  - Controls orbit locations (e.g., longitude for GEO) for satellites
  - Also has provided many technical standards for use in
    - SATCOM
    - Other radio environments, e.g., microwave LOS radios
- **In-Country Governmental Regulatory Body:**
  - Controls spectrum use within the country
  - **United States**:
    - **Federal Communications Commission (FCC)** manages non-government use
    - **National Telecommunications and Information Administration (NTIA)** manages Federal use of spectrum
  - **Foreign countries**: Formerly, the PTT (which was a part of government) typically also managed radio spectrum. Varies country to country
- **Purpose:**
  - Protect customers and assures efficient use of spectrum
    - Provides legal protection from interference from users on their systems or other systems
    - Satellite operators, e.g., work together to assure limited inter-system interference
- **Procedure:**
  - Users must typically coordinate with other systems and obtain license before beginning operations – outside the US, this is often termed obtaining “landing rights”

Major US SATCOM RF Frequency Bands

RF Band	Bandwidth	Downlink	Uplink
UHF: Military	5 & 25 KHz	243–270 MHz	292-319 MHz
C Band: (6/4 GHz)	500 MHz	3.7-4.2 GHz	5.925-6.425 GHz
X Band (8/7 GHz)	500 MHz	7.25-7.75 GHz	7.9-8.4 GHz
Ku Band: 14/11 GHz	500 MHz	10.95-12.75 GHz	13.75-14.5 GHz
Ka Band: 30/20 GHz			
Commercial Ka	2.5 GHz	17.7- 20.2 GHz	27.5-30 GHz
Military Ka	1 GHz	20.2-21.2 GHz	30-31 GHz
Military EHF: (44/20)	2 GHz up/1 down	20.2-21.2 GHz	43.5-45.5 GHz

Military RF Inter-Satellite Band: 5 GHz 59-64 GHz

Note: The exact RF band range for satellite use varies beween the three ITU Regions (US is in Region 2) & standard vs. extended band.

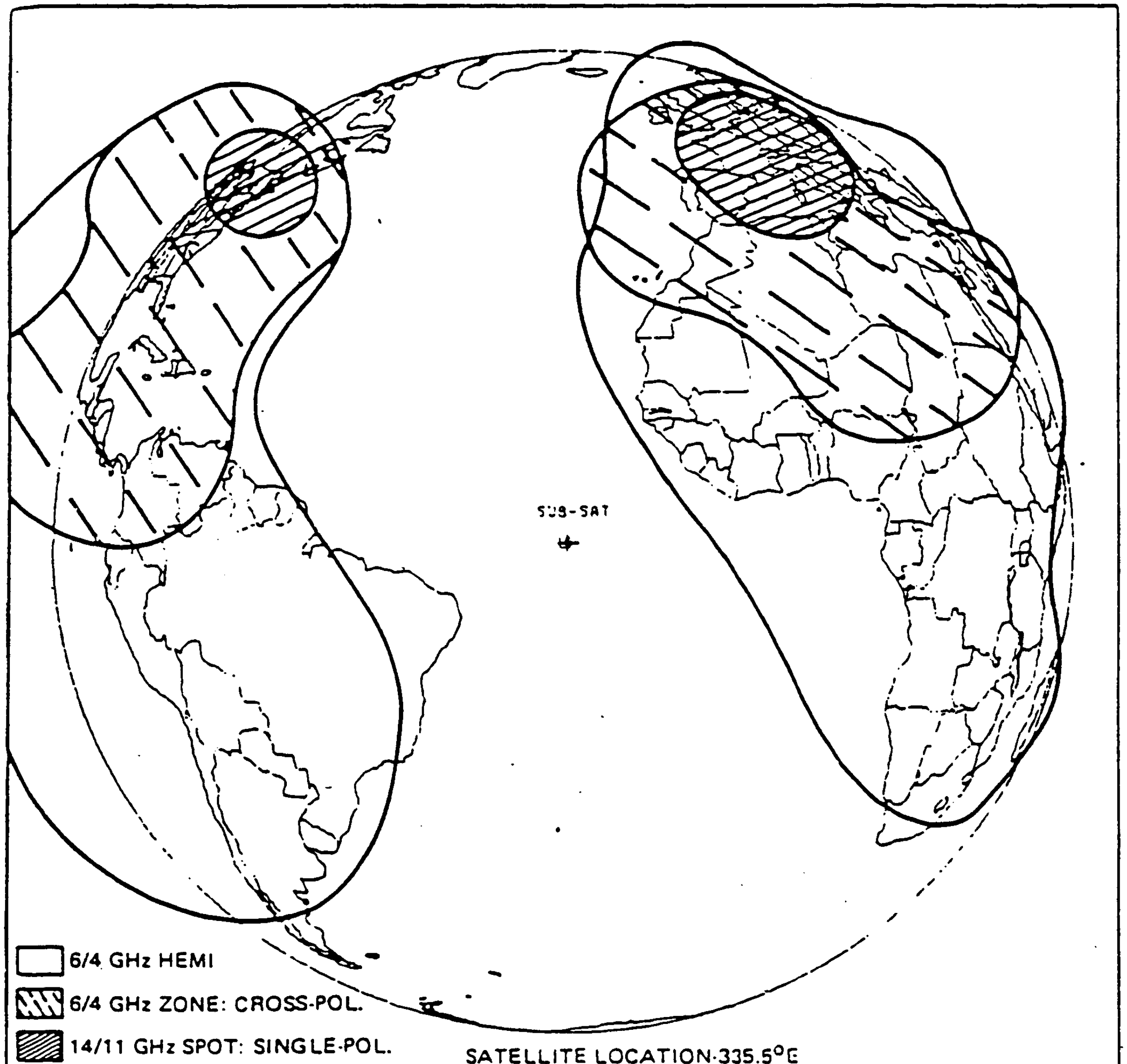
The above are <u>general</u> band designations used throughout industry and in this course.

These SATCOM band designations were adopted from radar band designations

Major Advantages of Satellite Communications

- **Interconnects users distributed across wide geographical areas**
- **Provides access for rural users with limited local terrestrial communications**
- **Easily supports broadcast to many terminals simultaneously**
  - **Based on satellite antenna footprint**
- **Provides reasonably wide bandwidths**
- **User terminals can be installed <u>very</u> <u>quickly</u>**
  - **Transportable/mobile terminals valuable for**
    - **Disaster support & recovery**
    - **Satellite Newsgathering (SNG trucks)**
    - **Early Deployment of troops in foreign areas**
  - **Transit case (TC) terminals can be checked as baggage on airplanes**

Current C/Ku Satellite Antenna Footprints Support Wide Connectivity Among Users



SATCOM Disadvantages and Potential Remedies

- Most communications satellites are in 23,000 miles high GEO orbits
  - Relatively large link signal loss and long transmission delay
    - Potential solutions:
      - Use large antennas and high power amplifiers
      - Use Performance Enhancing Protocols (PEPs) for TCP/IP links
  - Heavy rainfall causes link fading particularly at Ku/Ka RF bands
    - Potential solutions:
      - Use additional link margin
      - Use adaptive link data rate, or adaptive coding/modulation
      - Use site diversity
  - Interference can be a issue:
      - Co-channel interference due to operator errors
        - Other user is pointed at wrong satellite, on incorrect RF frequency or polarization
      - Adjacent satellite interference (ASI) from users with very small antennas
    - Potential solutions:
      - Work with satellite operator and NOC to determine source of interference and depend on operator to police your link per your lease agreement

Typical Transponder Services and Protection

- Example commercial satellite offerings:
  - Full period, 24/7
    - Monthly
    - Yearly
    - Multi-year – the longer the period, the lower the cost
  - Scheduled & recurring e.g., at 2-3 PM EST every day
  - Occasional use
    - Good example is a Satellite Newsgathering (SNG) truck
- Example levels of protection available for full time service:
  - Fully protected: in the event of transponder failure, protection of users by
    - Assignment of other pre-emptible transponders – same satellite
    - Assignment of other pre-emptible transponders – other satellites
  - Non-Pre-emptible: Cannot be pre-empted in case of other transponder failures
  - Pre-emptible: not protected ---- could be pre-empted in case of other transponder failures

II. Satellite Orbits

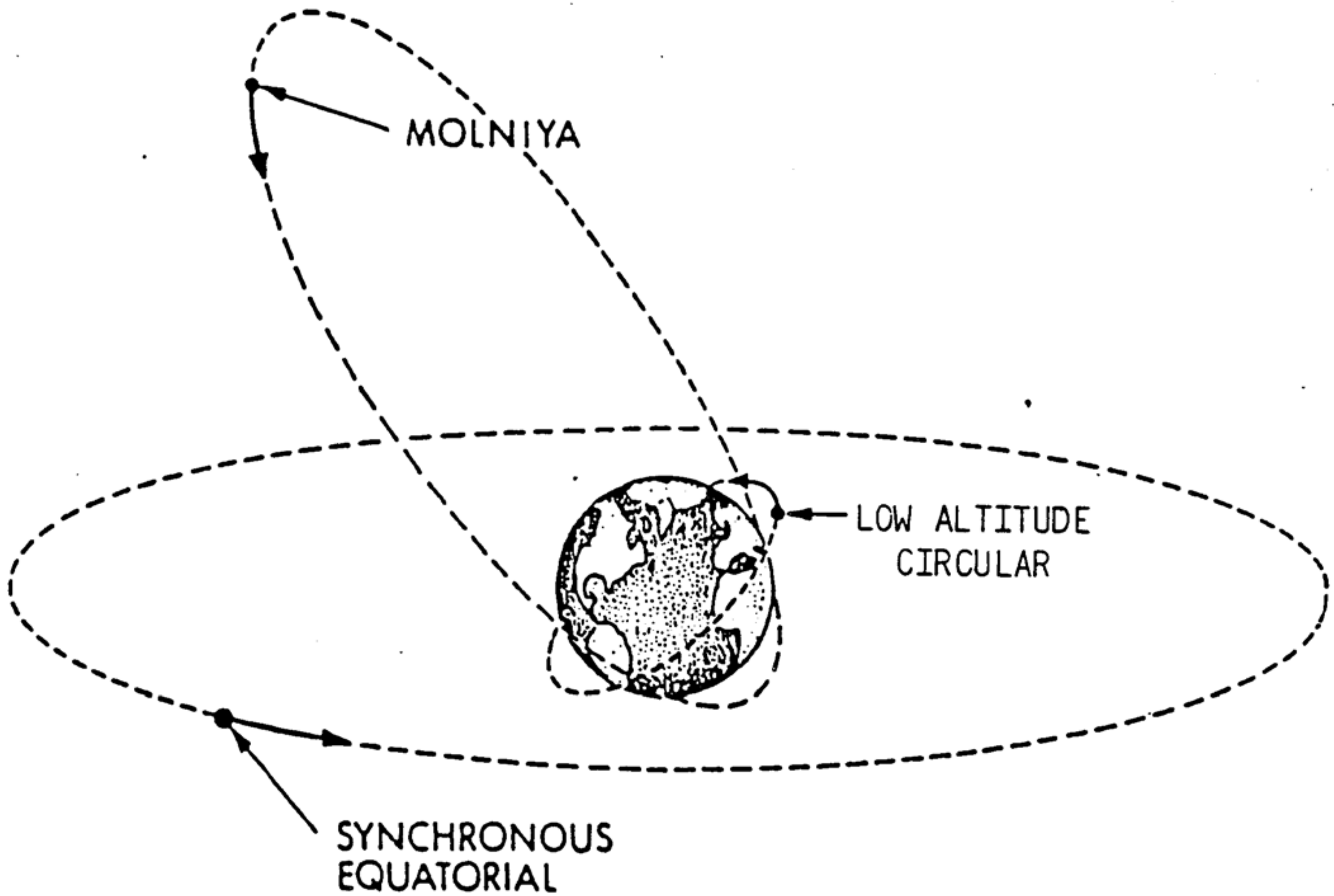
An Excellent Reference:

Roger Bate, Donald Mueller, Jerry White,
Fundamentals of Astrodynamics, Dover Publications, 1971

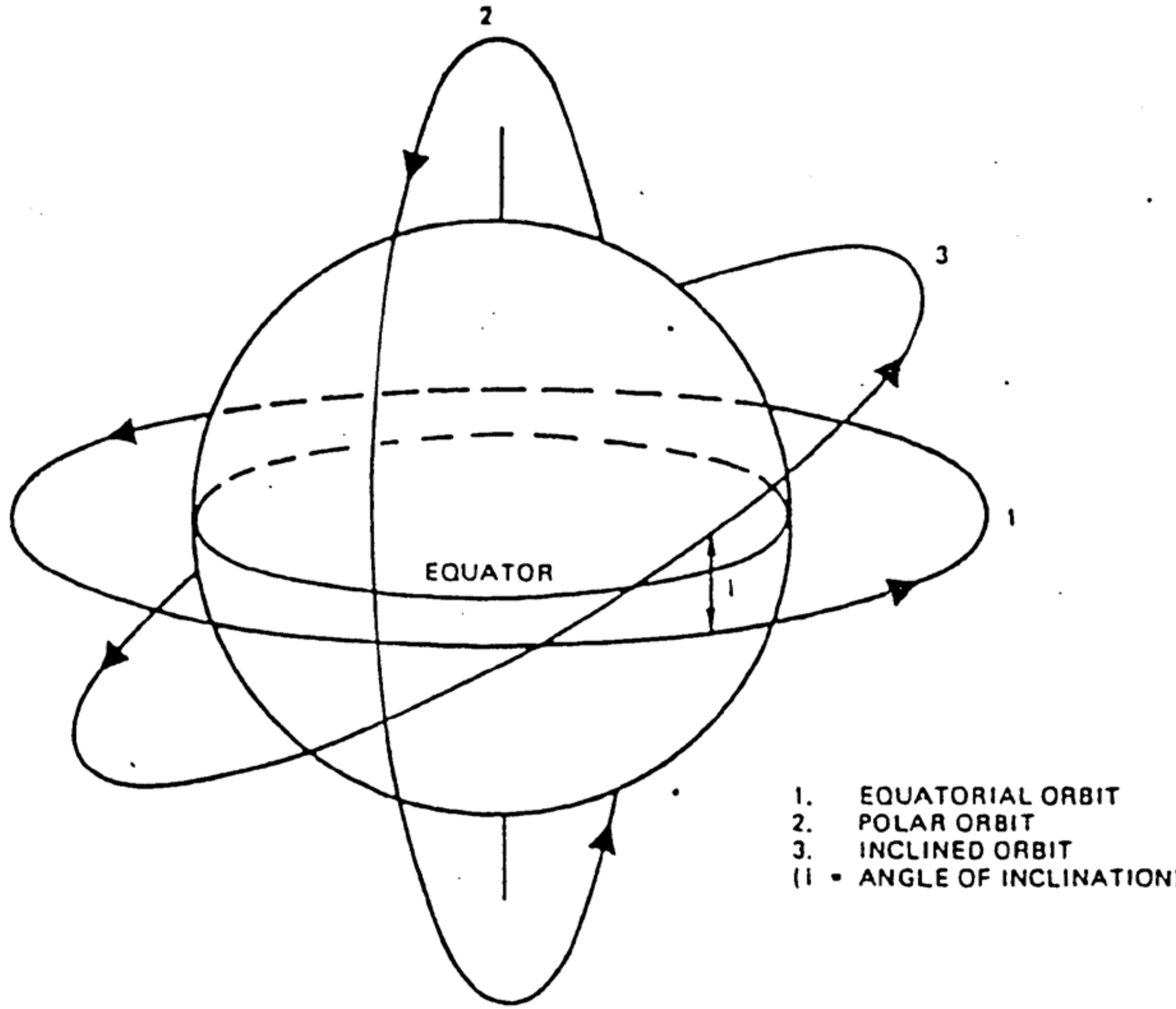
Classes of Satellite Orbits

- **Low Earth Orbit (LEO) --- defined as having altitude < 2000 km**
  - Circular, e.g., Iridium, Globalstar, Orbcomm; also many scientific, weather spacecraft
  - For comm use, a constellation of satellites is usually required to achieve reasonable visibility to users
  - A number of standard constellations of multiple satellites have been defined to meet certain objectives:
    - Walker constellations, etc.
    - Usually specified as, e.g., 7 spacecraft in each of 9 orbital planes at a specified inclination angle, equally spaced around the equator
- **Medium Earth Orbit (MEO)**
  - Circular, with altitudes from ~ 2,000 km out to 35786 km,
  - e.g., GPS is ~ “half-synchronous” with altitude of ~ 20,200 km
  - Not many communications satellites in this regime; also Van Allen belts are in MEO
- **Highly Elliptical Orbit (HEO)**
  - Elliptical orbits, e.g., Molniya, Tundra, primarily at 63.4^0 inclination
  - Achieves good visibility with high average elevation angles for users at high latitudes
- **Geosynchronous Earth Orbit (GEO)**
  - Circular, with altitude such that the orbital period exactly equals one sidereal period of the earth’s rotation
  - If excellent station-keeping is maintained, this could be called a “geostationary” orbit
  - By far the dominant orbit for communications satellites

General Cases of Orbital Geometry

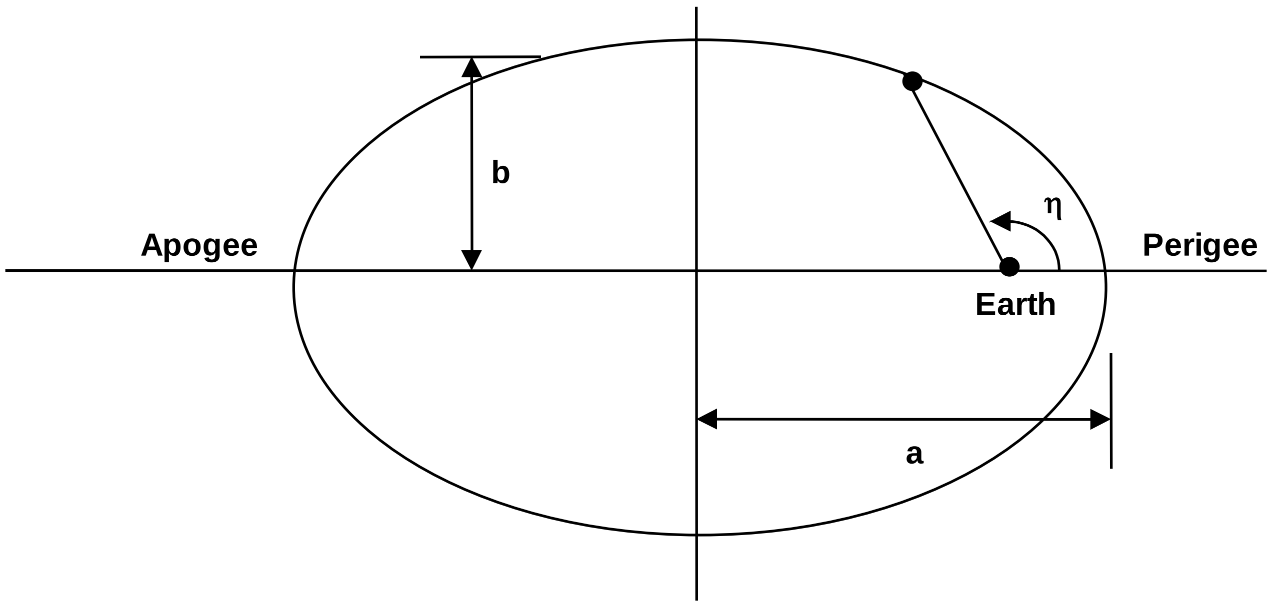


Common Names for Circular Orbits



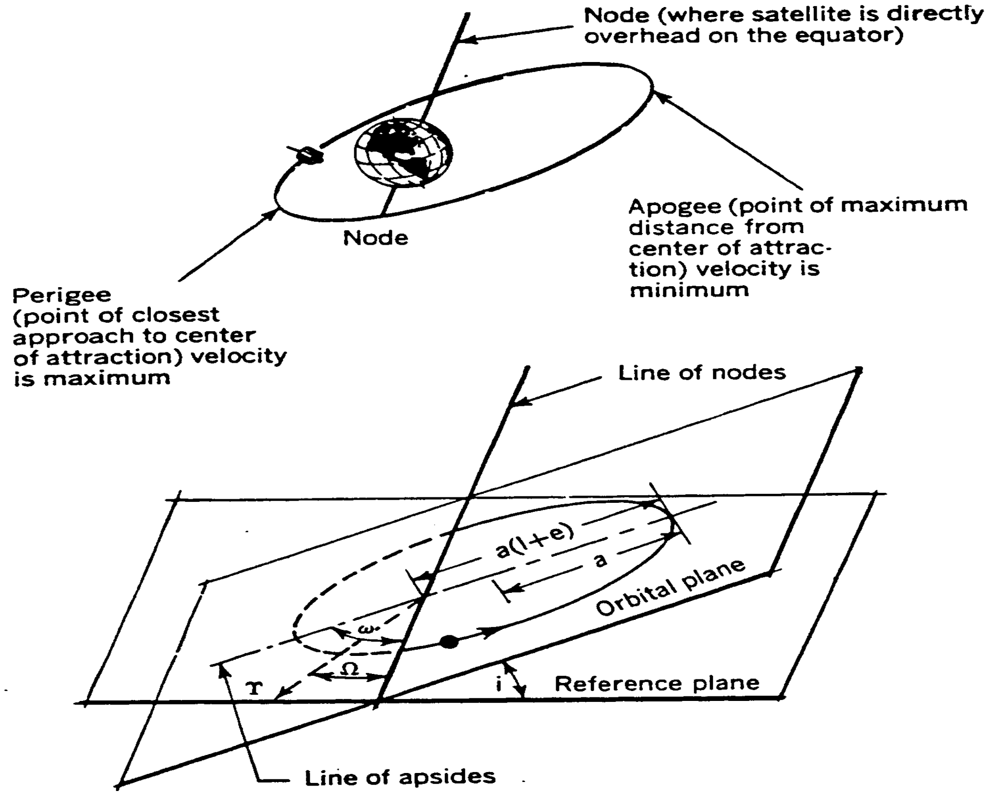
Three Parameters Describe Orbit Size and Shape

$$e = \left(1 - \frac{b^2}{a^2}\right)^{\frac{1}{2}}$$



- **Semi-Major axis, *a***
- **Eccentricity, *e***
- **True Anomaly, η**

Three Parameters Describe Orbit Orientation



- **Angle of Inclination, I**
  - **Angle between orbital and equatorial planes**
- **Right ascension of ascending node, Ω**
  - **Measured eastward in the equatorial plane from the vernal equinox**
- **Argument of Perigee, ω**
  - **Measured in orbital plane in the direction of the orbital motion from ascending node to line from earth center to perigee**

Communications-oriented Characteristics of Circular Orbits

- Orbital Period
- Coverage
- Time above the Horizon

Orbital Period for a Circular Orbit

- From Kepler's Laws we know that the orbital sidereal period is a function of satellite altitude:

$$T(\text{sec}) = [2\pi/\sqrt{GM_e}](r_e + h)^{3/2}$$

where r_e is the earth's radius, h is the satellite altitude, and

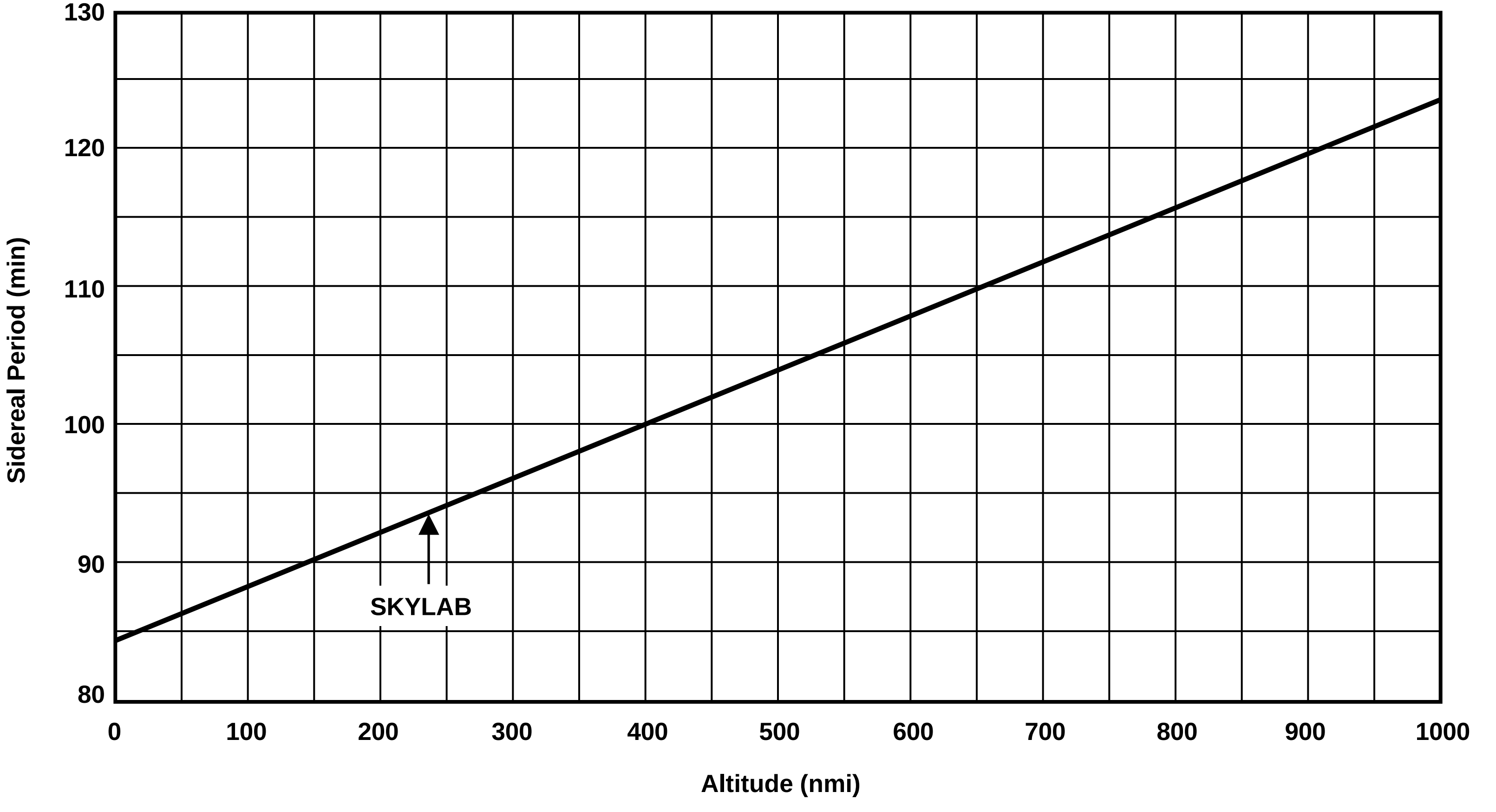
$$GM_e = 398{,}600.4418 \text{ km}^2/\text{s}^2$$

- Note that: r_e = 6378 km (or 3444 nm or 3963 sm)

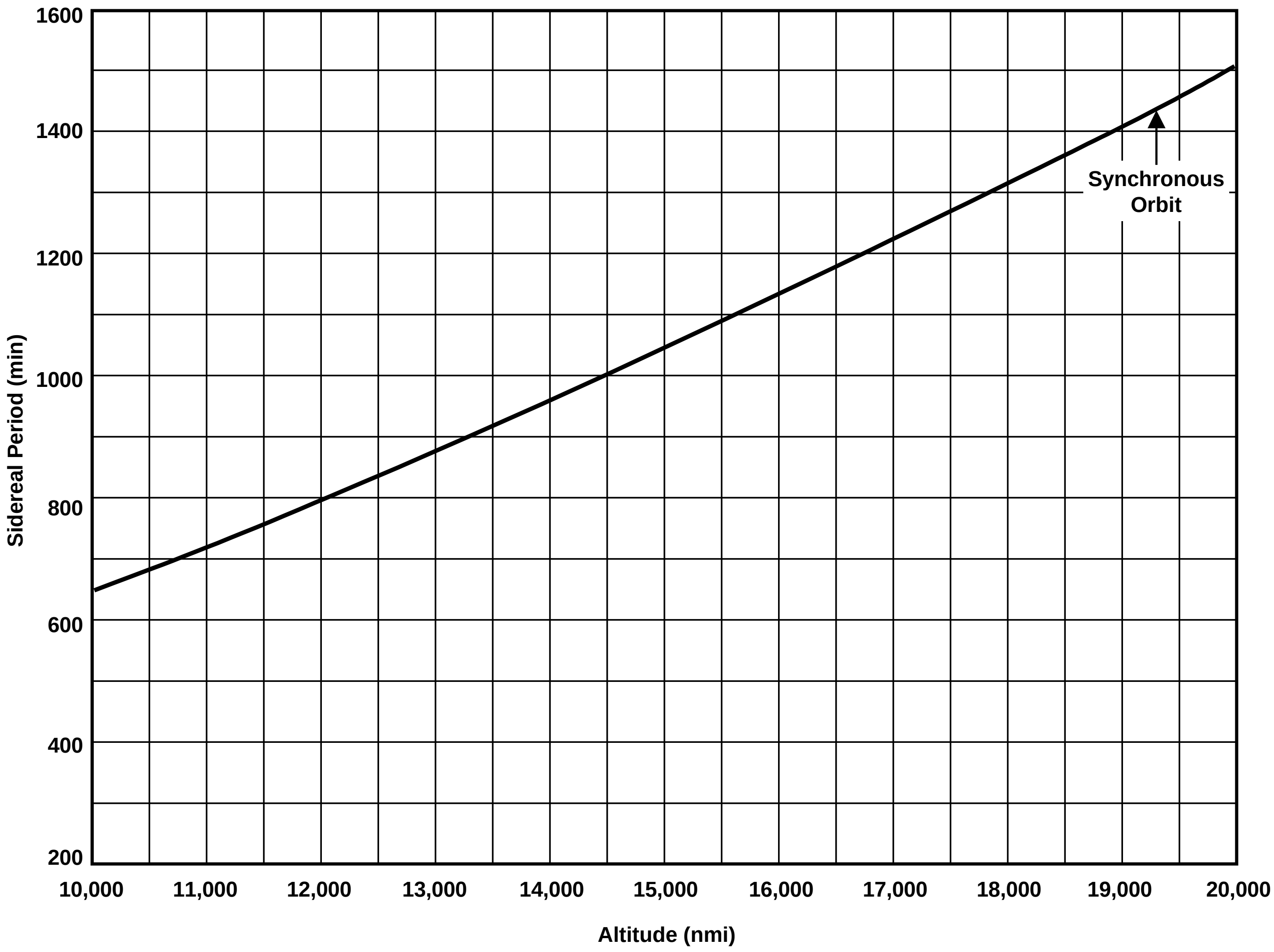
- For example, the period of a satellite whose altitude is zero (the so-called Herget orbit -- the absolutely minimum orbital period possible) would be:

$$T_H = 84.486 \text{ minutes}$$

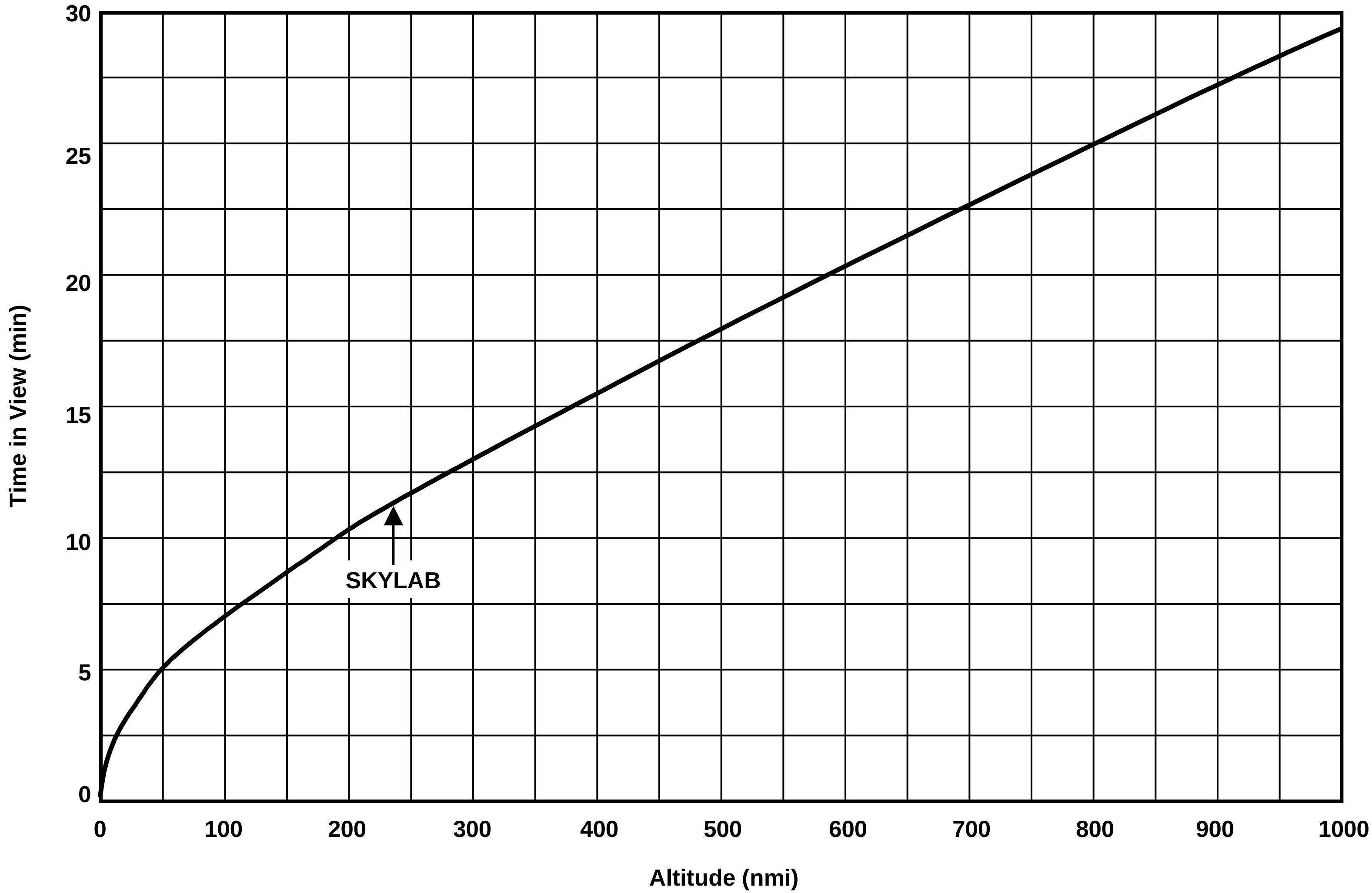
Sidereal Period vs. Low Altitude Satellite



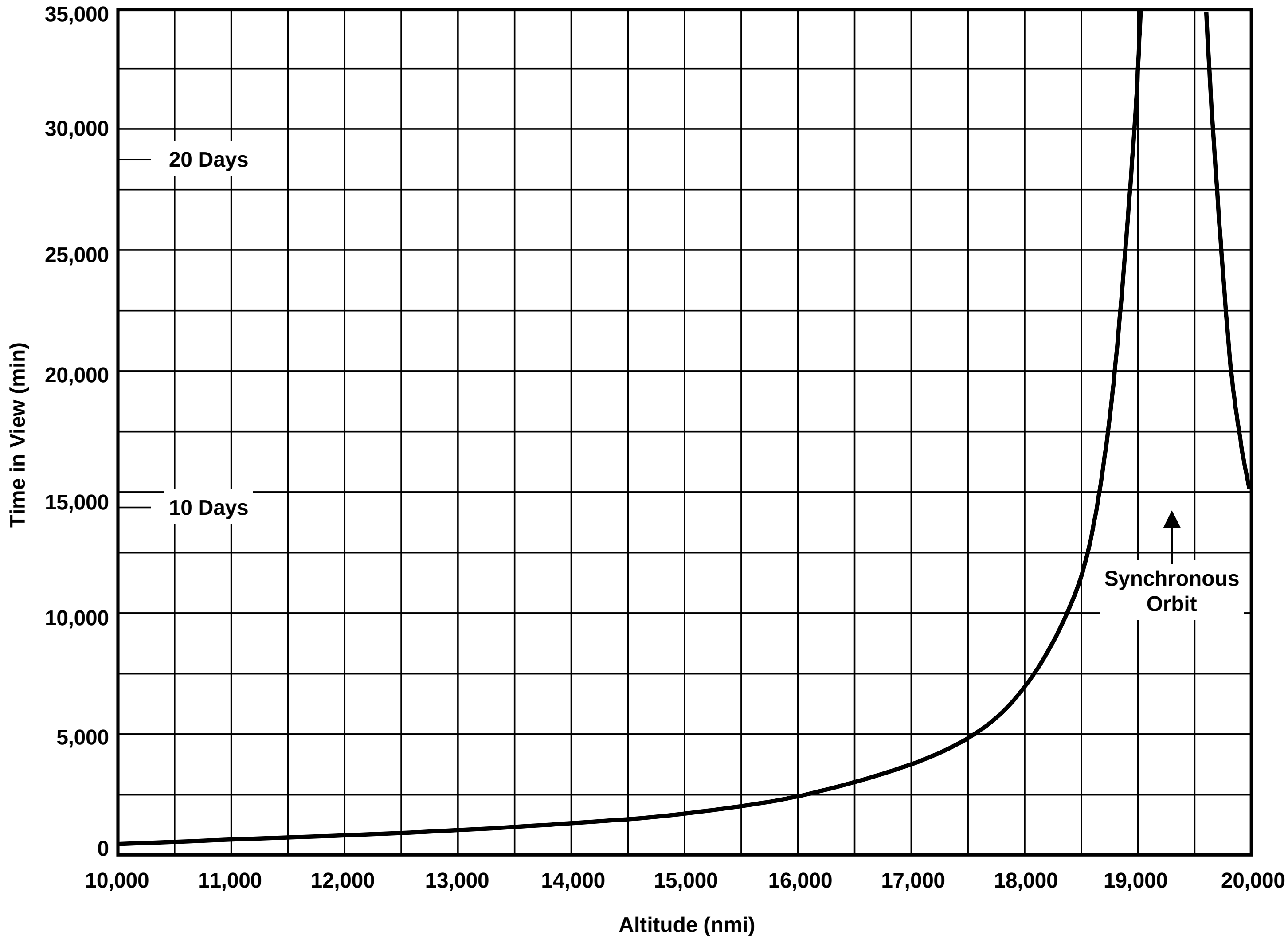
Sidereal Period vs. High Altitude Satellite



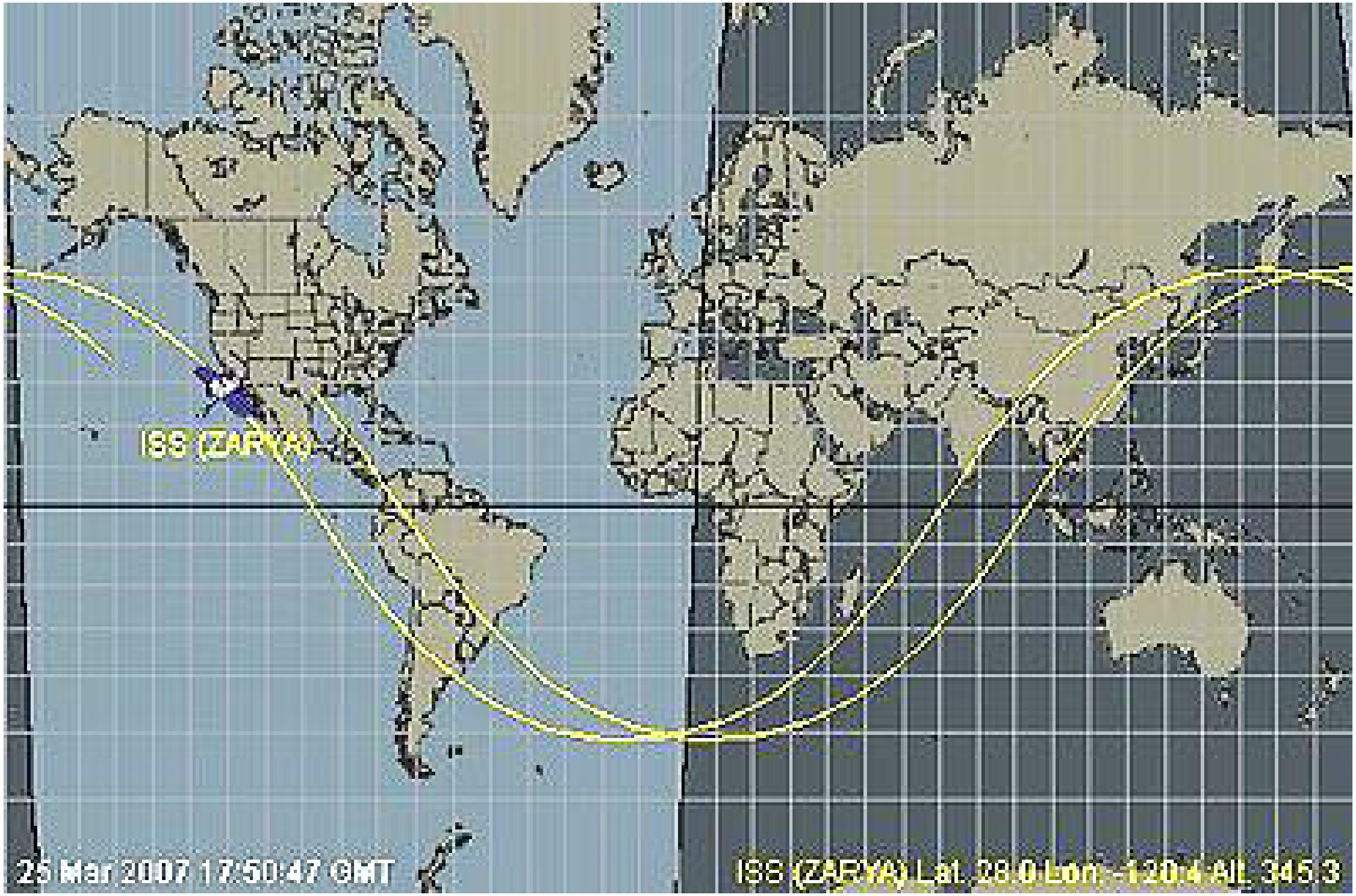
Maximum Visibility (Zenith Pass) for a LEO



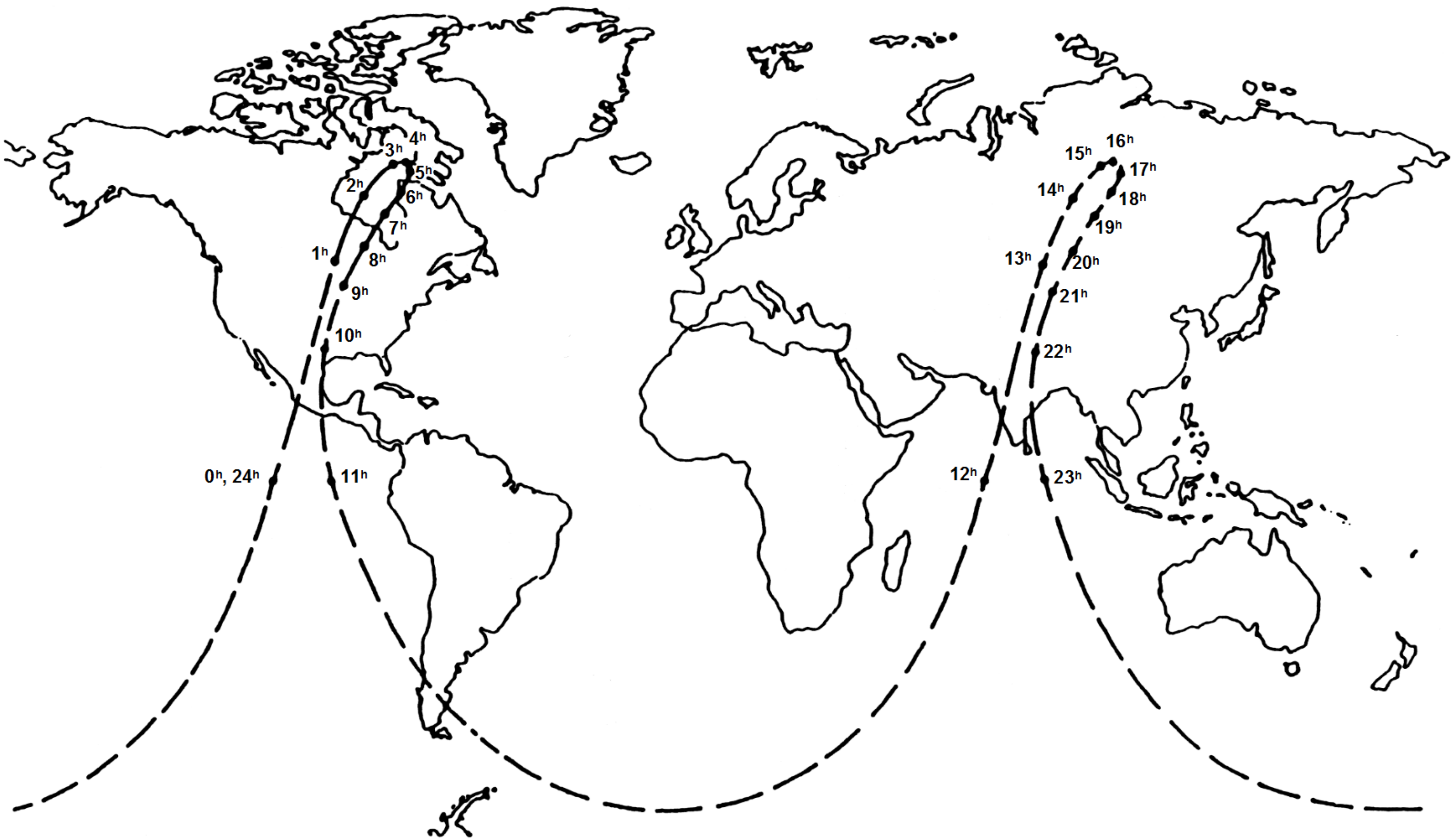
Maximum Visibility for a MEO/GEO Satellite



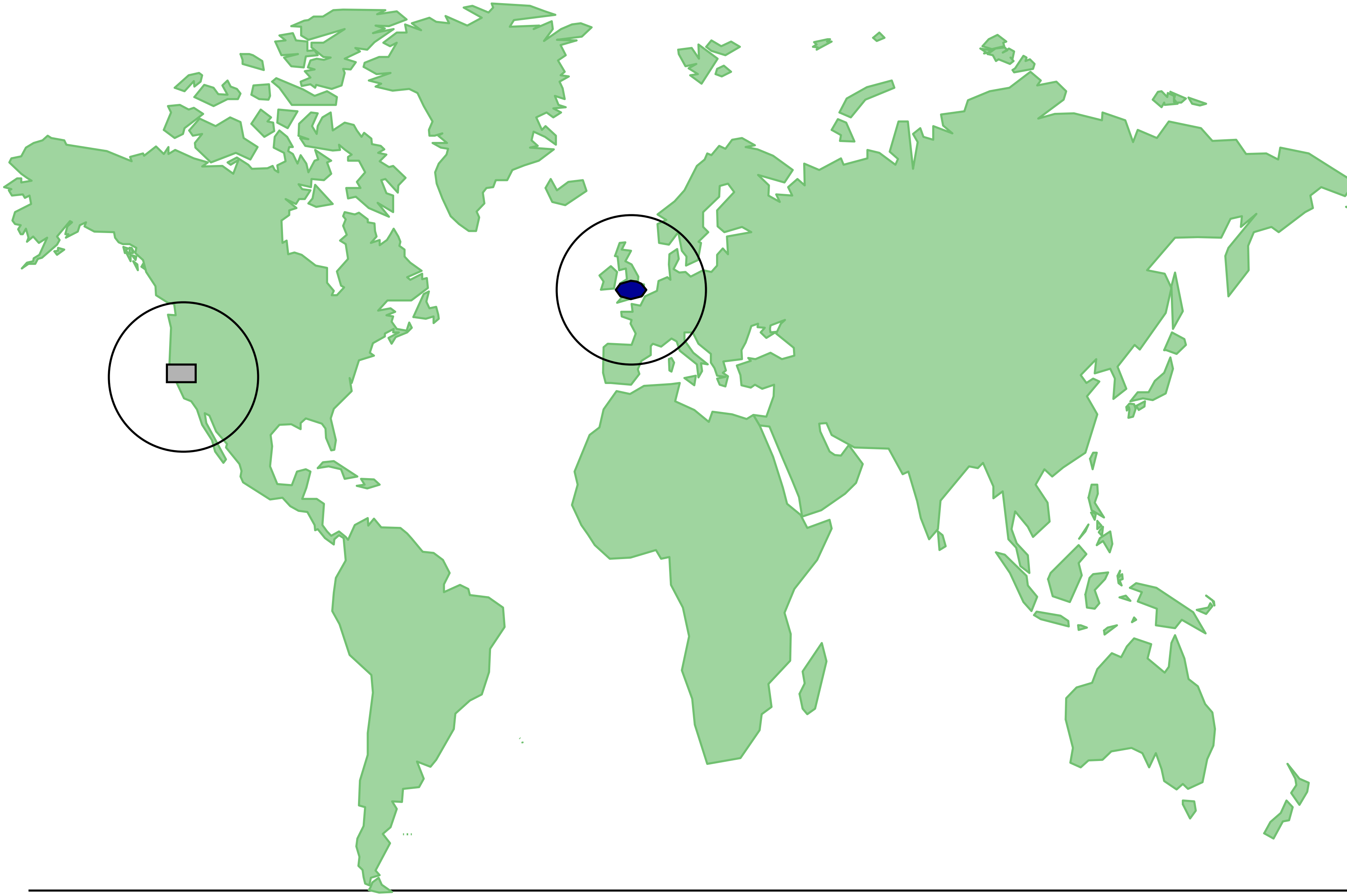
Example LEO Ground Trace: ISS (278<h< 460 km)



Example HEO Ground Trace: Molniya (e = 0.72)



“Station Circle” Size Depends on LEO Altitude & Minimum Allowed Terminal Elevation Angle



Implications of the Station Circle Geometry for LEOs

- Only users who are both within a station circle are able to <u>simultaneously</u> communicate directly via a LEO
  - Very limited geographic coverage for real time communications
  - Potential solutions for communicating using LEOs
    - Use store-and-forward techniques
      - Uplinked message is stored on board S/C and rebroadcast downlink when intended receiver comes into view
        - DoD (DARPA) had several LEO S/C in orbit at the start of First Gulf War (1991) and experimented with this approach:
        - MAC I, MAC II; MICROSAT – single plane of 6 small satellites
    - Use crosslinks between LEOs to relay the messages
      - Iridium took this approach
    - Implement lots of ground sites for coverage
      - Globalstar took this approach
- Many environmental & scientific satellites are in LEO orbit due to their sensor requirements and must communicate in one of two main ways:
  - Store telemetry and mission data as needed
    - Burst telemetry and mission data down and receive commands when their ground station(s) come into view
  - Use the Tracking & Data Relay Satellite System (TDRSS) as a GEO relay

Spacecraft Velocity Depends on Orbit Altitude

- The linear velocity of a spacecraft in circular orbit can be found from the circumference of the orbit and the orbital period:

$$v = 2\pi(r_e+h)/T$$

$$= 631.35/(r_e+h)^{1/2}$$

  - So, for a 300 km orbit, v = 7.73 km/sec
  - For a GEO orbit, (r_e+h= 42,223 km), v = 3.07 km/sec

- The velocity of a spacecraft in an elliptical orbit <u>at</u> <u>perigee</u> can be higher than the velocity of a spacecraft in the lowest circular orbit, or as high as ~ 10 km/sec

Geosynchronous Orbits

Geosynchronous Satellite Orbit Altitude

From Kepler's Law:

$$T = [2\pi/(GM_e)^{1/2}](r_e + h)^{3/2}$$

where r_e is the earth's radius, h is the satellite altitude, and

$$GM_e = 398{,}600.4418\ km^2/s^2 \quad \text{(typically designated as } \mu\text{)}$$

Thus for a satellite whose orbital period is equal to 1 sidereal day (23 hours, 59 minutes, 4 seconds, or 86,344 sec)

$$r_e + h = 42{,}223\ km \text{ or } 23{,}093\ nm, \text{ or } 26{,}242\ sm$$

Thus the altitude of a <u>Geosynchronous</u> satellite is

$$h = 42{,}223\ km - 6378\ km = 35845\ km$$

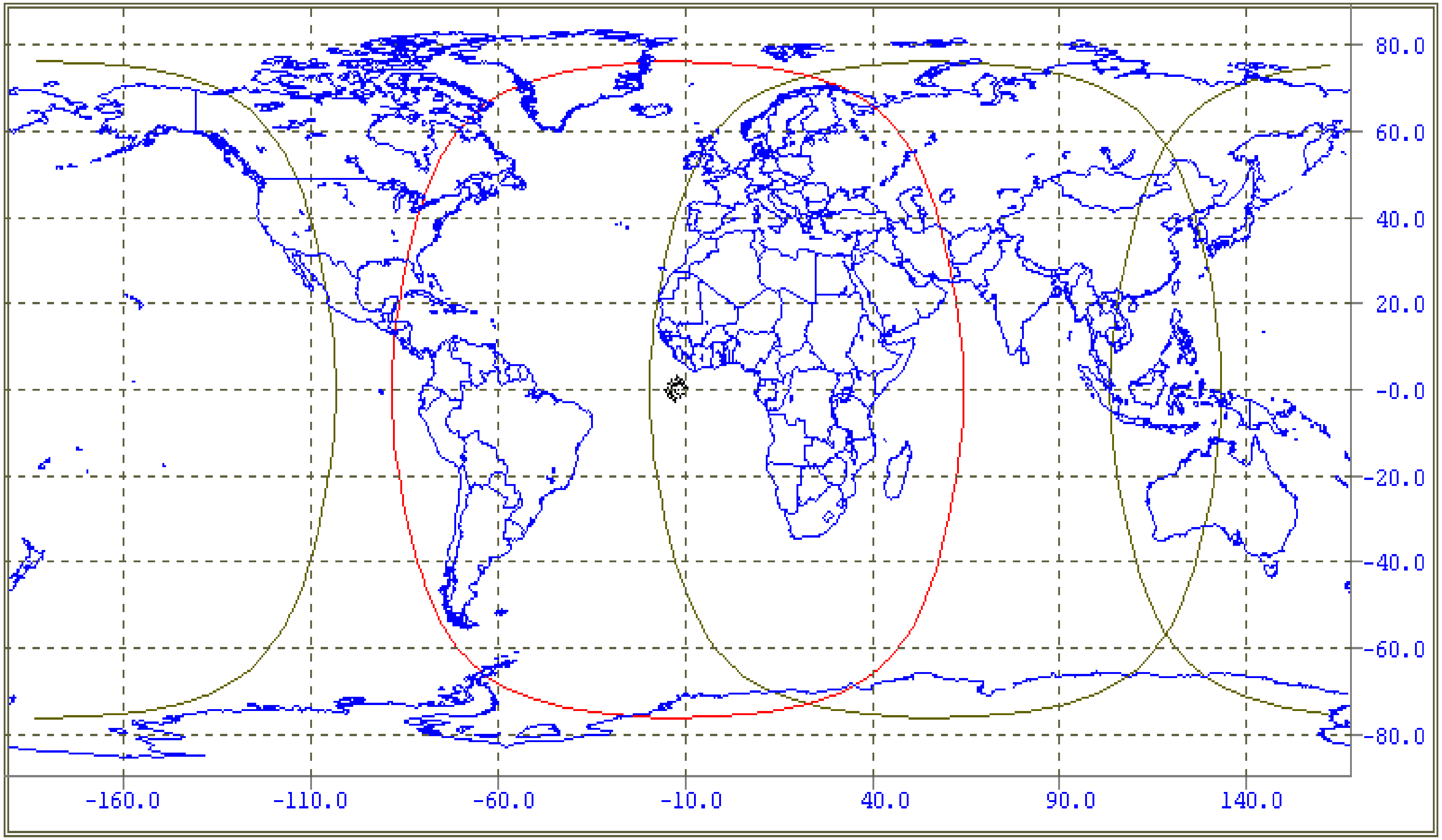
or

$$h = 23{,}093\ nm - 3444\ nm = 19{,}649\ nm$$

or

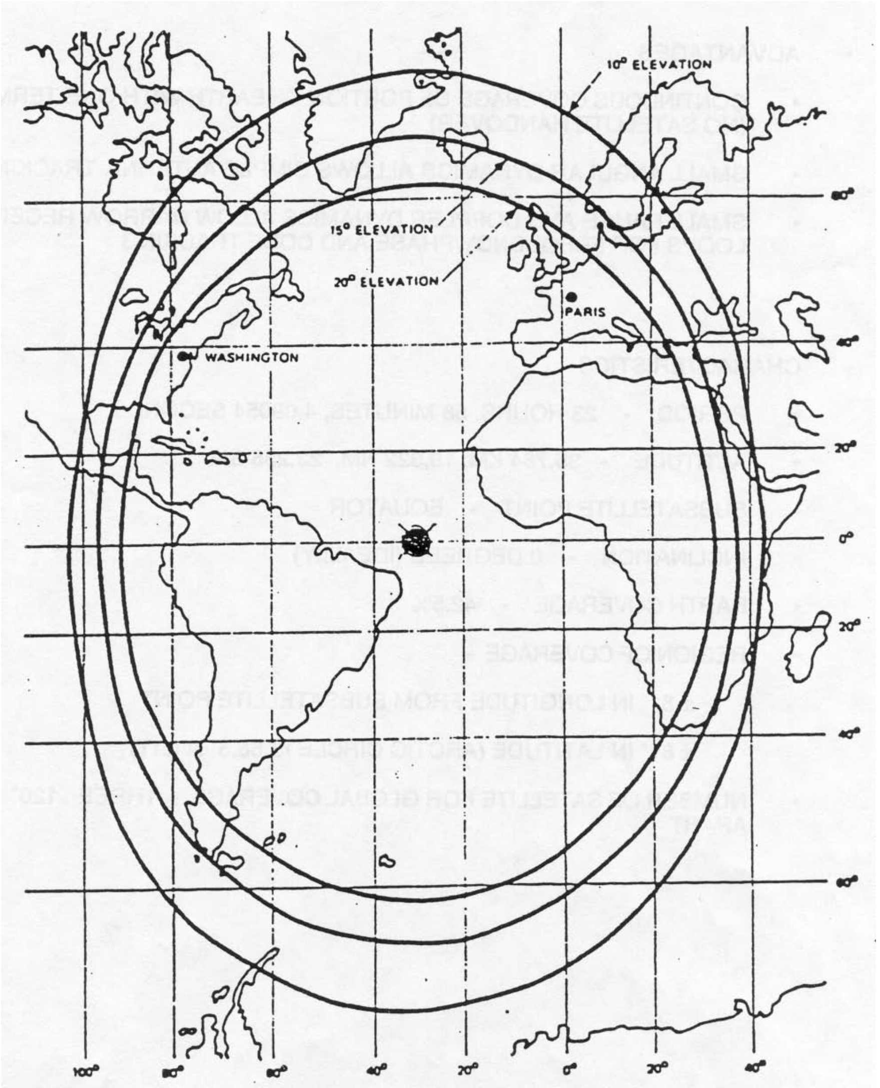
$$h = 26{,}242\ sm - 3963\ sm = 22{,}279\ sm$$

"3-Ball" GEO Constellation and its Geometric Coverage



But spacecraft antenna footprints will determine actual coverage

Potential GEO Coverage Varies Slightly with Terminal's Elevation Angle



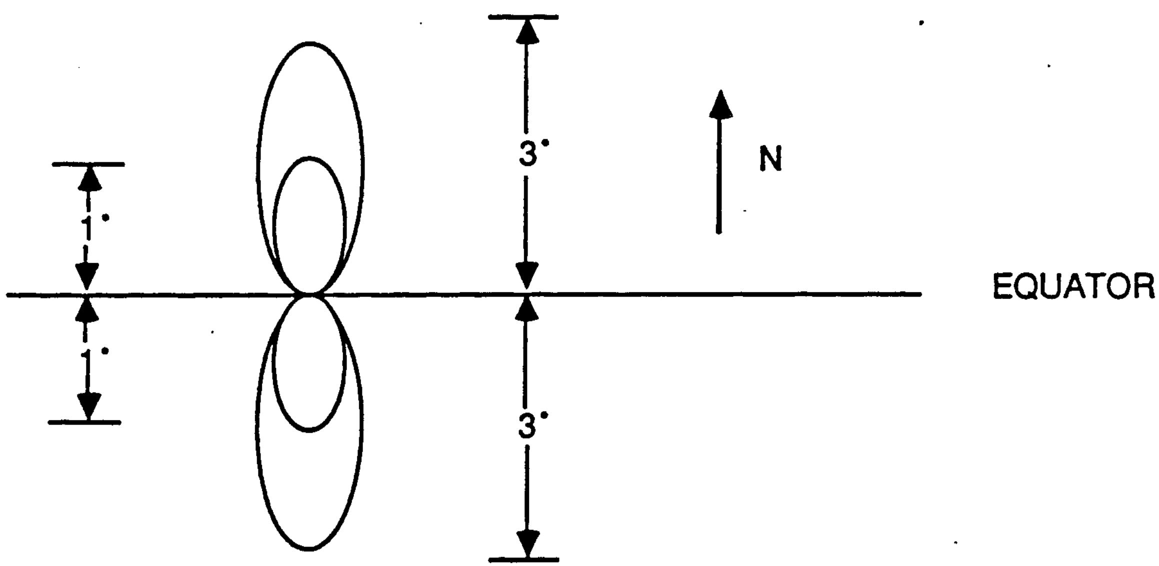
Perturbations from the Ideal GEO Orbit

- There are three major perturbations (plus other smaller influences) that require expenditure of Δv for station-keeping:
  - Gravitational action of the moon and the sun
  - Earth's triaxiality (non-sphericality)
  - Solar radiation pressure
- The major perturbation is the precession of the orbital plane causing it to increase over 26 years to about 15^0 before returning back to 0^0
  - Inclination can increase at about 0.850 initially
- "Gravity wells" exist due to the ellipticity of the equator that would affect a GEO E-W station-keeping that should be corrected:
  - A GEO would tend to move toward one of the two stable points at:
    - 75.3^0 E and 104.7^0 W (Himalayas and Rockies)
  - A GEO would tend to move away from one of the two unstable points at:
    - 165.3^0 E and 14.7^0 W (Marshall Islands and Portugal)
- Station-keeping fuel necessary to maintain the assigned longitude and to minimize inclination angle of the orbital plane can add 10-40% to the dry mass of a GEO; fuel is measured in units of change in velocity, Δv.
  - N-S station-keeping requires Δv ~50 m/s per year; E-W up to 2 m/s per year
  - Some satellites have also been launched with ion-thrusters

“Figure 8” Movement of a GEO Satellite

- **If a GEO’s orbital plane has an inclination angle with respect to the equatorial plane equatorial plane ≠ 0, then its subsatellite point on the earth’s surface, traces out a figure 8 pattern on the earth’s surface:**
  - **The figure 8 repeats every 24 hours**
  - **The N-S dimension of the figure 8 increases as the inclination increases**
  - **The sun and moon would cause an uncorrected GEO to increase up to ~15^0 inclination**

- **Example Figure 8 ground trace of the nadir point:**

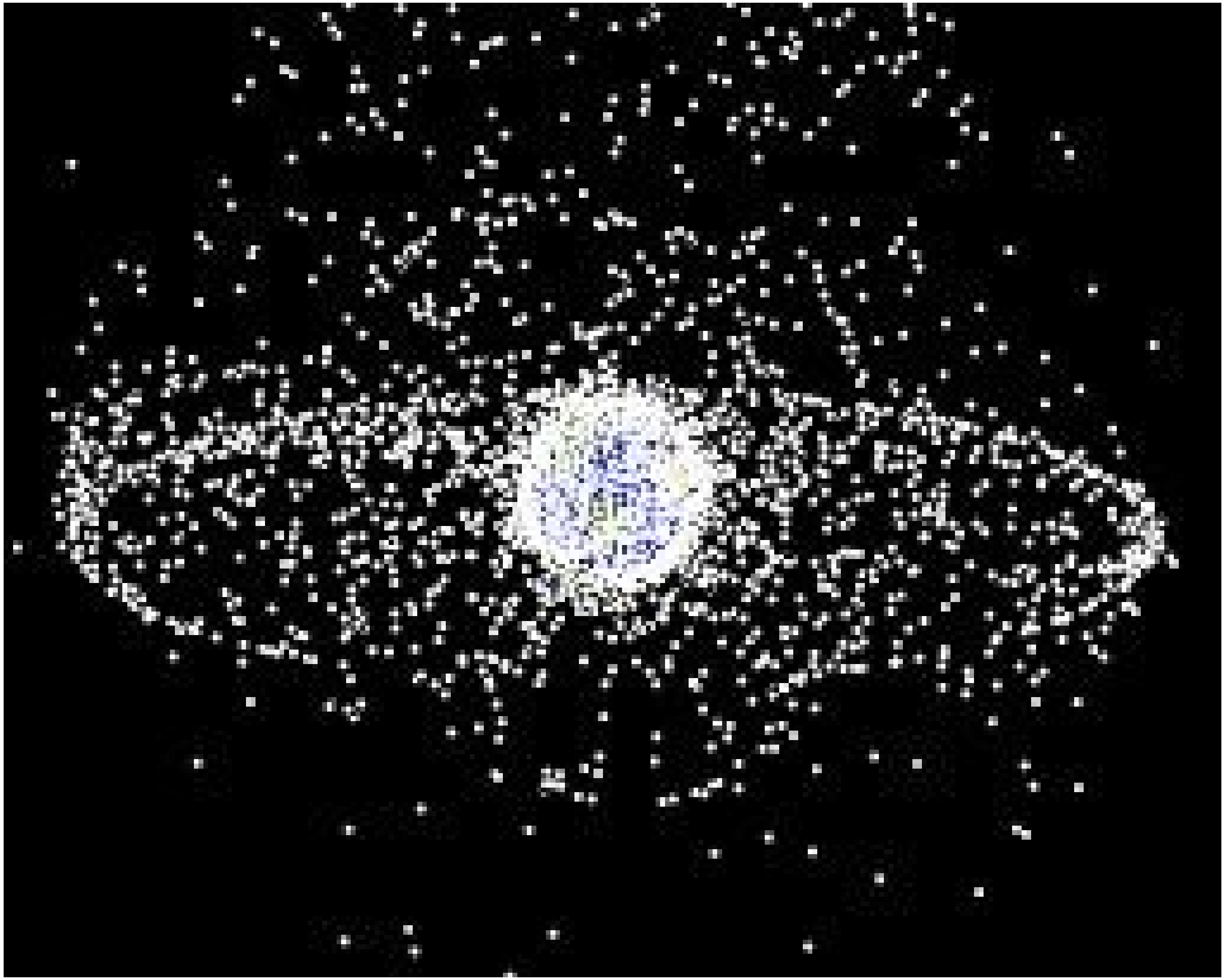


Inclined Orbit Operations

- Since station-keeping fuel is the major determinant of normal spacecraft operational life, one approach to extending the operations of a GEO is to:
  - Reduce expenditure of station-keeping fuel by not correcting (very often) for orbital inclination angle and allow figure 8 movement to increase
  - Allow inclination angles up to 3-5^0 or more
  - Use of the patented “Comsat Maneuver” made Inclined Orbit Operations feasible by compensating for footprint movement with changing motion of the spacecraft
- Major drawback is that earth station antennas (with narrow beamwidths) would be required to track the satellite’s movement
  - However the slow Figure 8 movement over a 24 hour period can be tracked by relatively inexpensive tracking systems

Orbital Debris

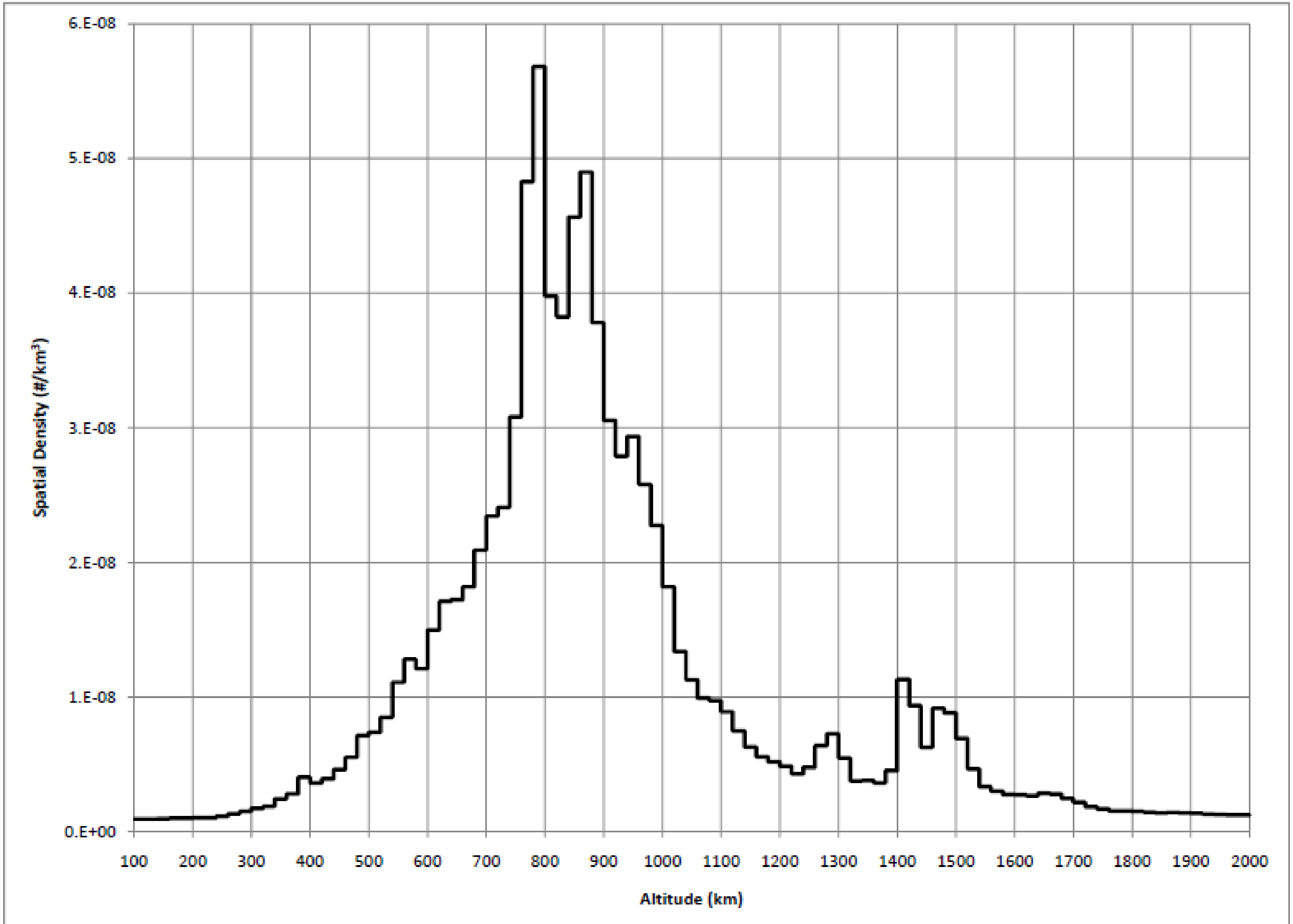
One Representation of Only the Largest Space Objects



Overview of the Orbital Debris Problem

- Since Sputnik there have been ~ 5000 space missions
- Number of debris fragments > 1 cm size estimated to be > 500,000
- Total objects now officially cataloged by the DoD is ~ 34,000, of which ~ 13,000 are still in orbit + ~ 5,000 that are being tracked but not cataloged
  – The unpredicted collision of Iridium 33 and COSMOS 2251 in February 2009 resulted in the addition of > 1500 large (> 10 cm) pieces of debris
    - Concentrated near 800 km but extending from 200-1700 km
- Approximately 1300 objects are satellites but only ~ 800 have fuel and can be moved if necessary to avoid a collision
- Space Surveillance Network can track objects larger than ~ 10 cm in LEO orbit up to ~ 2000 km altitude
  – 10 cm debris at 5-7 km/sec can do terrific damage
  – The next generation Space Fence is required to track up to 200,000 objects in LEO orbit vs. current Space Fence tracking of 20,000 objects
- Other sensors can do much better than 10 cm but are not available full time
  – E.g., NASA Solar System Radar at Goldstone (70m) can detect mm-size debris in LEO orbit
- At GEO, the minimum estimated size routinely tracked is ~ 70 cm

Histogram of Cataloged Objects as of 5 June 2009



US Government Guidelines for Disposal

- Operational lifetime limited to 25 years
- Spacecraft or upper stage must be disposed of by one of three methods:
  - LEO Orbits: Atmospheric Reentry Option
    - Maneuver to orbit in which, using conservative projections for solar activity, atmospheric drag will limit lifetime to < 25 years after completion of mission; risk of human casualty should be
      < 1 in 10,000
  - "Storage" Orbit
    - Between LEO and MEO: Maneuver to an orbit with perigee altitude above 2000 km and apogee altitude below 19,700 km (500 km below semi-synchronous, e.g., where GPS is)
    - Between MEO and GEO: Maneuver to an orbit with perigee altitude above 20,700 km and apogee altitude below 35,300 km (500 km above semi-synchronous and 500 km below synchronous altitude
  - GEO: See next slide
- Direct Retrieval: Unlikely with current technology

Inter-agency Space Debris Coordination (IADC) Committee Guidelines on GEO Disposal

- A GEO should retain enough fuel to be maneuvered into an orbit above the GEO protected region fulfilling the following two conditions:
  - A minimum increase in perigee altitude of

$$235 \text{ km} + (1000 \times C_R \times A/m), \text{ where}$$

C_R is the solar radiation pressure coefficient

A/m is aspect area to dry mass ratio (m^2/kg^{-1})

235 km is the sum of :

200 km (upper altitude of GEO protected region) &

35 km (max. descent of re-orbited s/c due to luni-solar & geopotential perturbations)

  - An eccentricity of ≤ 0.003 (added in 2007)

- Bottom line: 300 km above nominal GEO altitude is typically used
- In addition: Operators should passivate all spacecraft stored energy sources:
  - Chemical: vent chemicals, burn excess fuels, relieve pressure vessels
  - Electrical: discharge batteries

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