Enhanced GPS Accuracy using Lunar Transponders

G. Konesky
SGK NanoStructures, Inc.

LEAG - ICEUM - SSR
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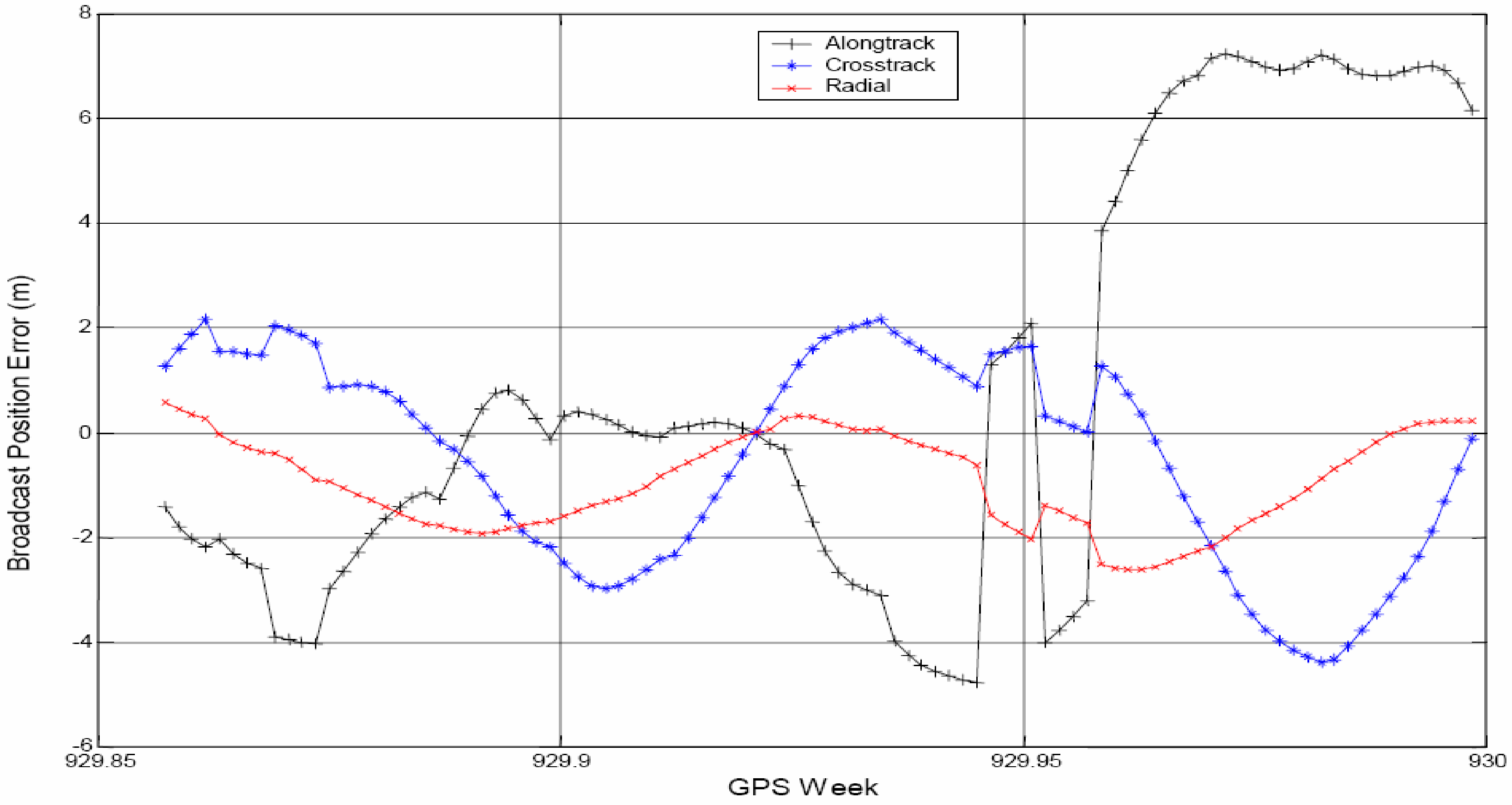
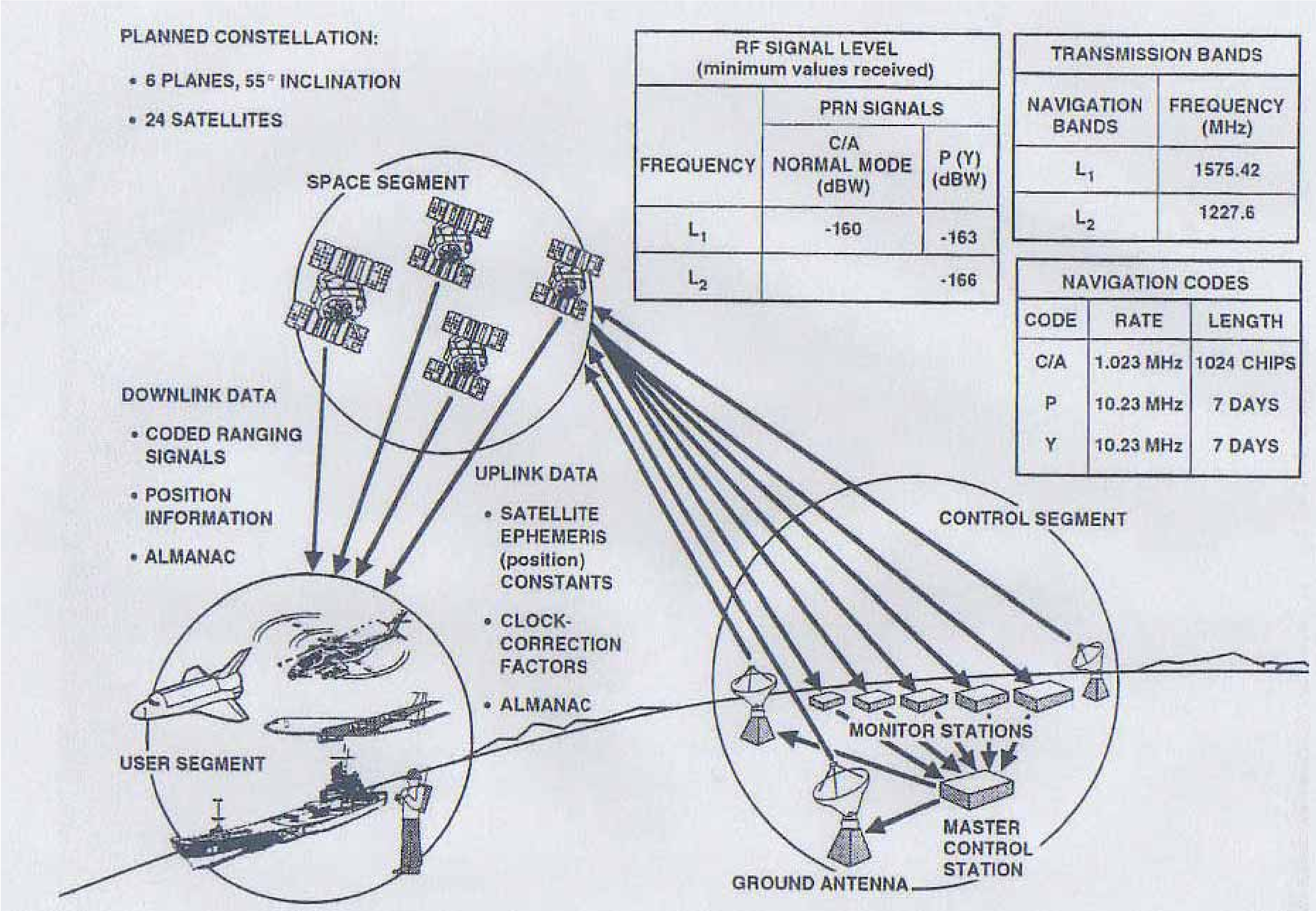
GPS Broadcast Ephemeris Error



Nov. 1, 1997

Warren, 2002



PLANNED CONSTELLATION:

- 6 PLANES, 55° INCLINATION
- 24 SATELLITES

DOWNLINK DATA

- CODED RANGING SIGNALS
- POSITION INFORMATION
- ALMANAC

UPLINK DATA

- SATELLITE EPHEMERIS (position) CONSTANTS
- CLOCK-CORRECTION FACTORS
- ALMANAC

RF SIGNAL LEVEL (minimum values received)

FREQUENCY	PRN SIGNALS	
	C/A NORMAL MODE (dBW)	P (Y) (dBW)
L_1	-160	-163
L_2		-166

TRANSMISSION BANDS

NAVIGATION BANDS	FREQUENCY (MHz)
L_1	1575.42
L_2	1227.6

NAVIGATION CODES

CODE	RATE	LENGTH
C/A	1.023 MHz	1024 CHIPS
P	10.23 MHz	7 DAYS
Y	10.23 MHz	7 DAYS

Warren, 2002

Other Navigation Satellites

Glonass

Kiranana, 2007

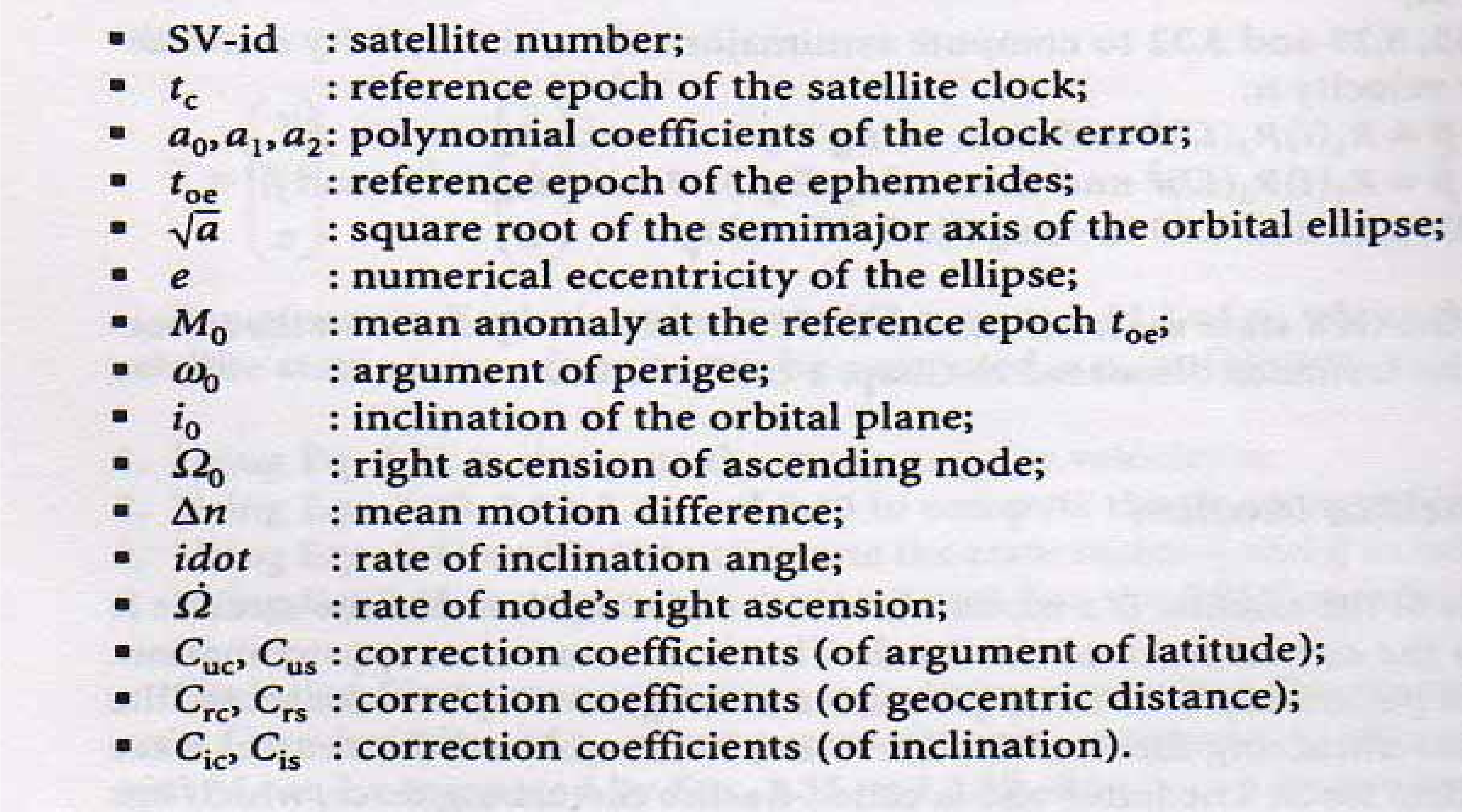
Other Navigation Satellites

Galileo

ESA, 2006

Characteristic	GPS	GLONASS	Galileo
First launch	February 22, 1978	October 12, 1982	December 28, 2005
Full operational capability	July 17, 1995	January 18, 1996	2012/2013 (1)
Funding	public	public	public & private
Nominal number of SV	24	24	27
Orbital planes	6	3	3
Orbit inclination	55°	64.8°	56°
Semimajor axis	26 560 km	25 508 km	29 601 km
Orbit plane separation	60°	120°	120°
Phase within planes	irregular	±30°	±40°
Revolution period	11h 57.96 min	11h 15.73 min	14h 4.75 min
Ground track repeat period	~1 sidereal day	~8 sidereal days	~10 sidereal days
Ground track repeat orbits	2	17	17
Ephemerides data	Kepler elements, correction coefficients	position, velocity, acceleration vectors	Kepler elements, correction coefficients
Geodetic reference system	WGS-84	PE-90	GTRF
Time system	GPS time, UTC (USNO)	GLONASS time, UTC(SU)	Galileo system time
Leap seconds	no	yes	no
Signal separation	CDMA	FDMA	CDMA
Number of frequencies	3 – L1, L2, L5	one per two antipodal SV	3(4) – E1, E6, E5(E5a, E5b)
Frequency [MHz]	L1: 1 575.420 L2: 1 227.600 L5: 1 176.450	G1: 1 602.000 G2: 1 246.000 G3: 1 204.704 (1)	E1: 1 575.420 E6: 1 278.750 E5: 1 191.795

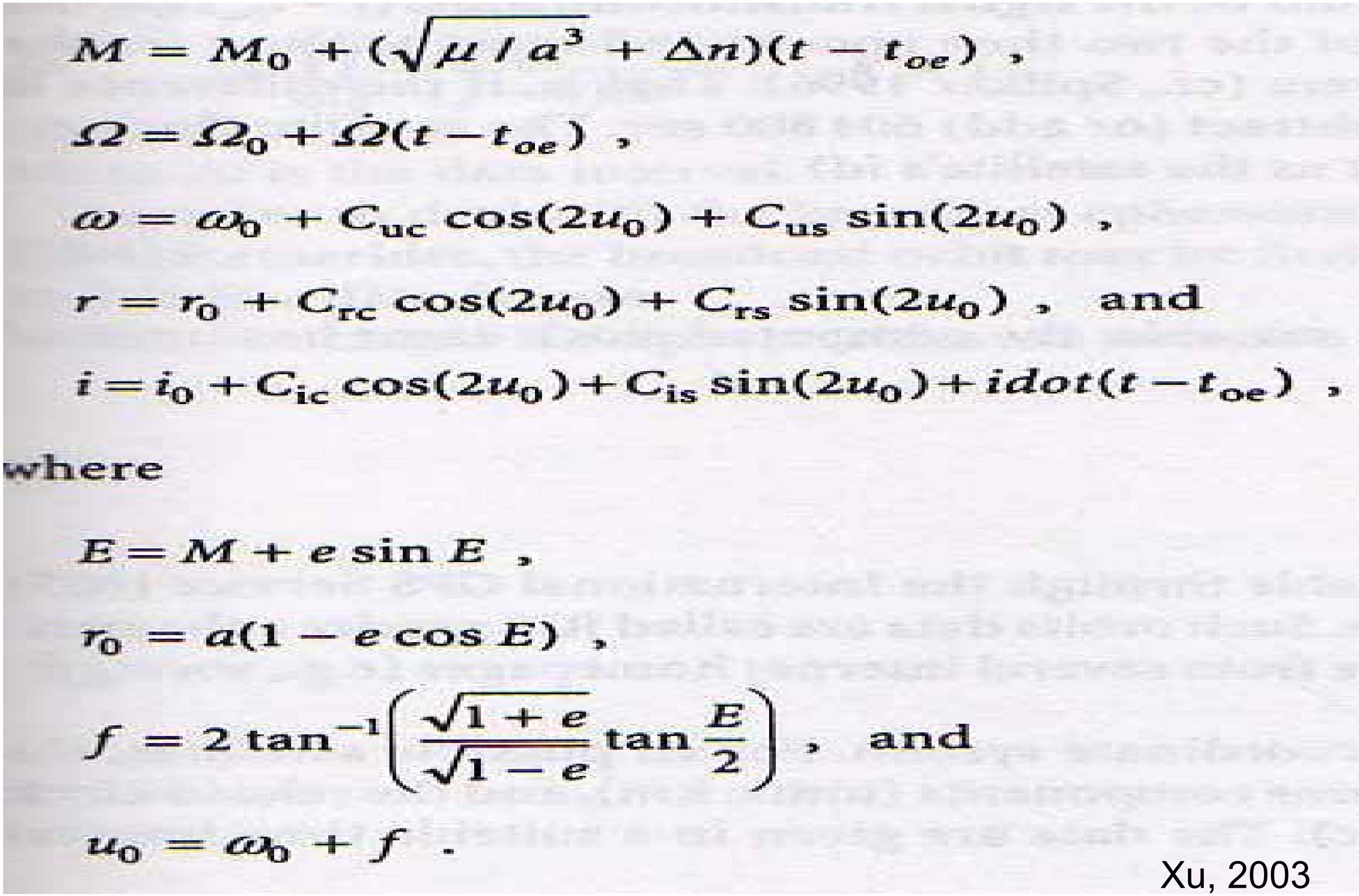
Ephemeris Parameters



- SV-id : satellite number;
- t_c : reference epoch of the satellite clock;
- a_0, a_1, a_2: polynomial coefficients of the clock error;
- t_{oe} : reference epoch of the ephemerides;
- $\sqrt{a}$: square root of the semimajor axis of the orbital ellipse;
- e : numerical eccentricity of the ellipse;
- M_0 : mean anomaly at the reference epoch t_{oe};
- ω_0 : argument of perigee;
- i_0 : inclination of the orbital plane;
- Ω_0 : right ascension of ascending node;
- Δn : mean motion difference;
- $idot$: rate of inclination angle;
- $\dot{\Omega}$: rate of node's right ascension;
- C_{uc}, C_{us} : correction coefficients (of argument of latitude);
- C_{rc}, C_{rs} : correction coefficients (of geocentric distance);
- C_{ic}, C_{is} : correction coefficients (of inclination).

Xu, 2003

Ephemeris Equations



$$M = M_0 + (\sqrt{\mu / a^3} + \Delta n)(t - t_{oe}) \ ,$$

$$\Omega = \Omega_0 + \dot{\Omega}(t - t_{oe}) \ ,$$

$$\omega = \omega_0 + C_{\mathrm{uc}} \cos(2u_0) + C_{\mathrm{us}} \sin(2u_0) \ ,$$

$$r = r_0 + C_{\mathrm{rc}} \cos(2u_0) + C_{\mathrm{rs}} \sin(2u_0) \ , \quad \text{and}$$

$$i = i_0 + C_{\mathrm{ic}} \cos(2u_0) + C_{\mathrm{is}} \sin(2u_0) + idot(t - t_{\mathrm{oe}}) \ ,$$

where

$$E = M + e \sin E \ ,$$

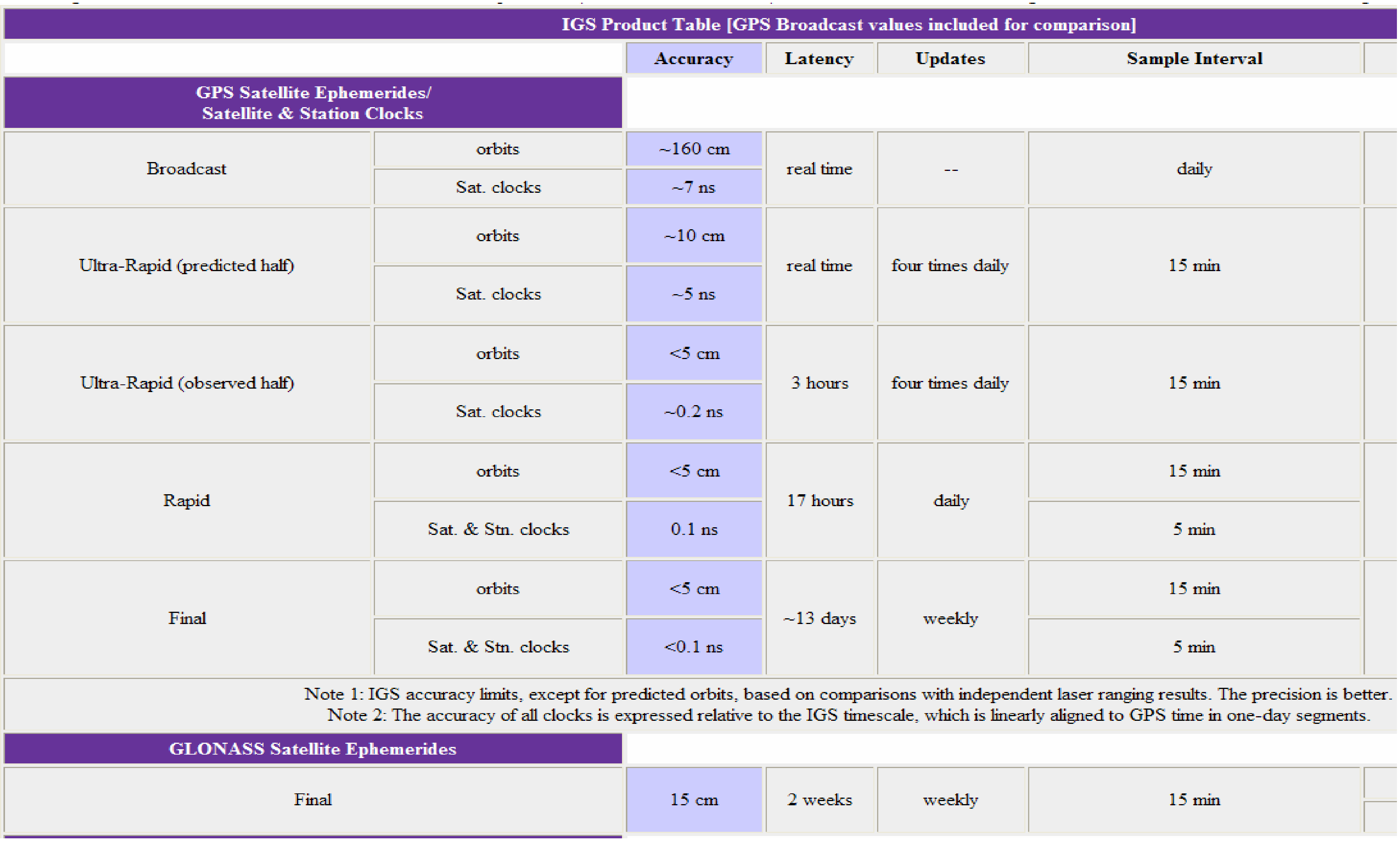
$$r_0 = a(1 - e \cos E) \ ,$$

$$f = 2 \tan^{-1}\left(\frac{\sqrt{1+e}}{\sqrt{1-e}} \tan \frac{E}{2} \right) \ , \quad \text{and}$$

$$u_0 = \omega_0 + f \ .$$

Xu, 2003

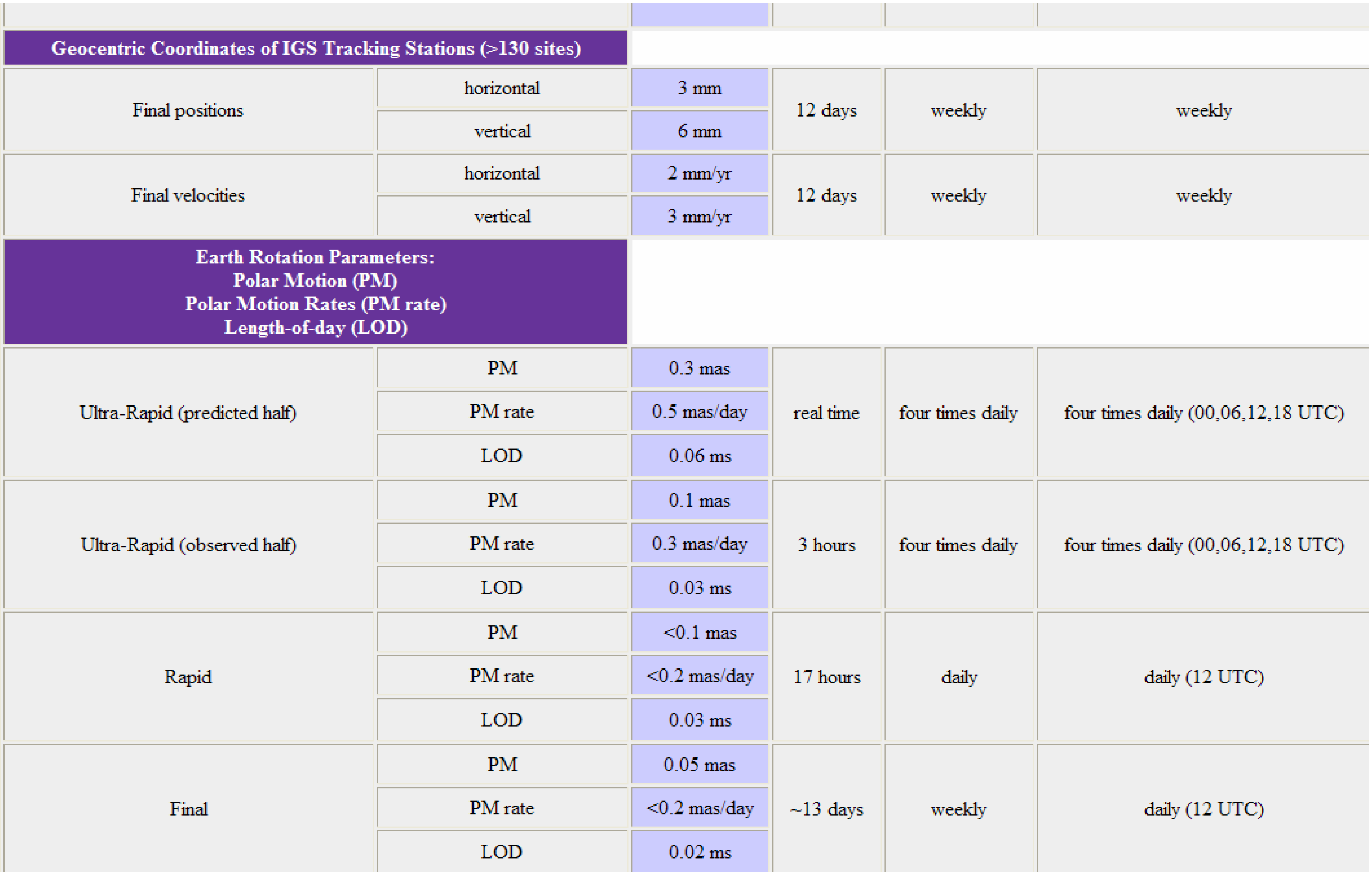
International GPS Service (IGS) Forecast Precise Ephemerides



IGS Product Table [GPS Broadcast values included for comparison]

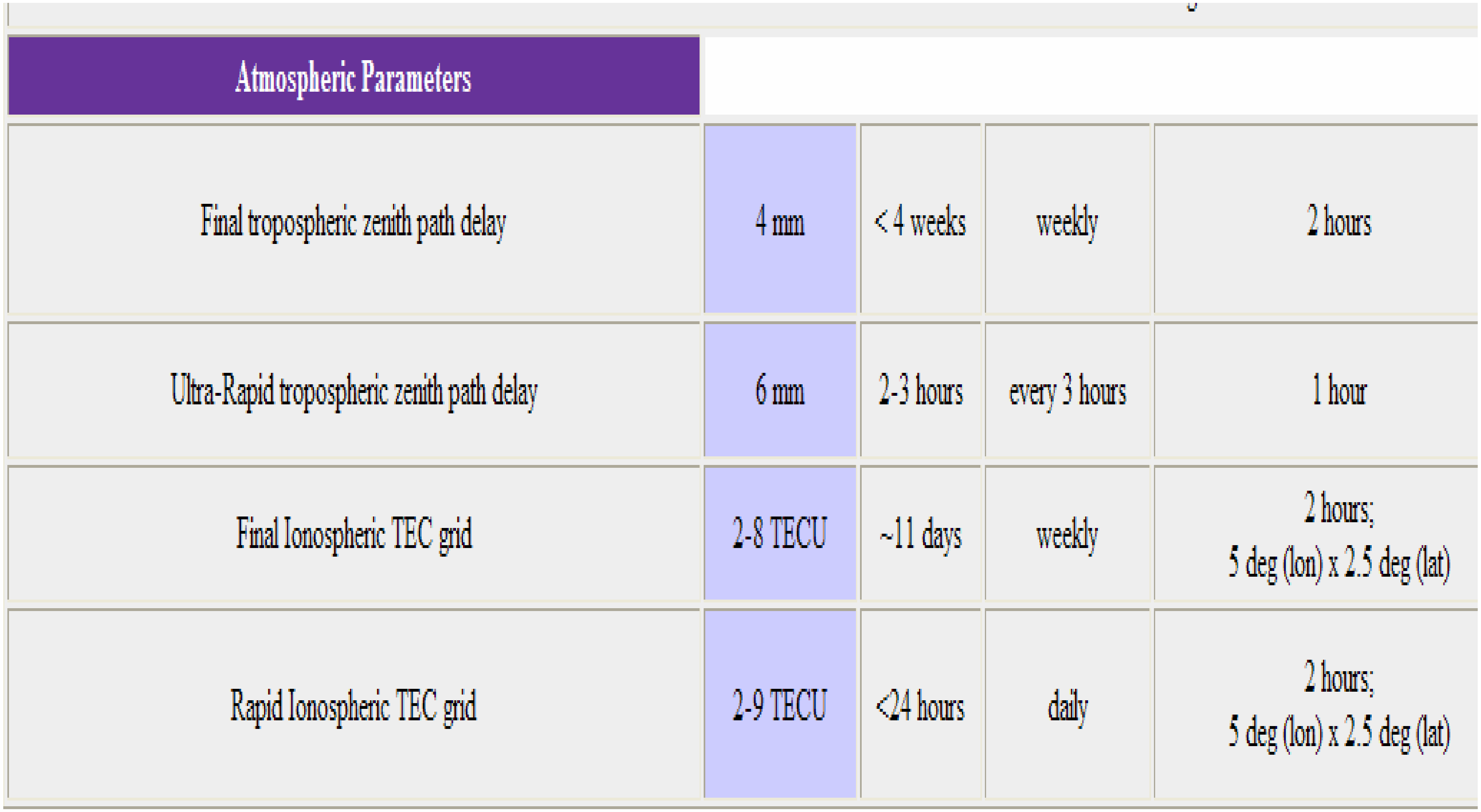
		Accuracy	Latency	Updates	Sample Interval
GPS Satellite Ephemerides/ Satellite & Station Clocks					
Broadcast	orbits	~160 cm	real time	--	daily
	Sat. clocks	~7 ns			
Ultra-Rapid (predicted half)	orbits	~10 cm	real time	four times daily	15 min
	Sat. clocks	~5 ns			
Ultra-Rapid (observed half)	orbits	<5 cm	3 hours	four times daily	15 min
	Sat. clocks	~0.2 ns			
Rapid	orbits	<5 cm	17 hours	daily	15 min
	Sat. & Stn. clocks	0.1 ns			5 min
Final	orbits	<5 cm	~13 days	weekly	15 min
	Sat. & Stn. clocks	<0.1 ns			5 min
Note 1: IGS accuracy limits, except for predicted orbits, based on comparisons with independent laser ranging results. The precision is better. Note 2: The accuracy of all clocks is expressed relative to the IGS timescale, which is linearly aligned to GPS time in one-day segments.					
GLONASS Satellite Ephemerides					
Final		15 cm	2 weeks	weekly	15 min

International GPS Service (IGS) Forecast Precise Ephemerides



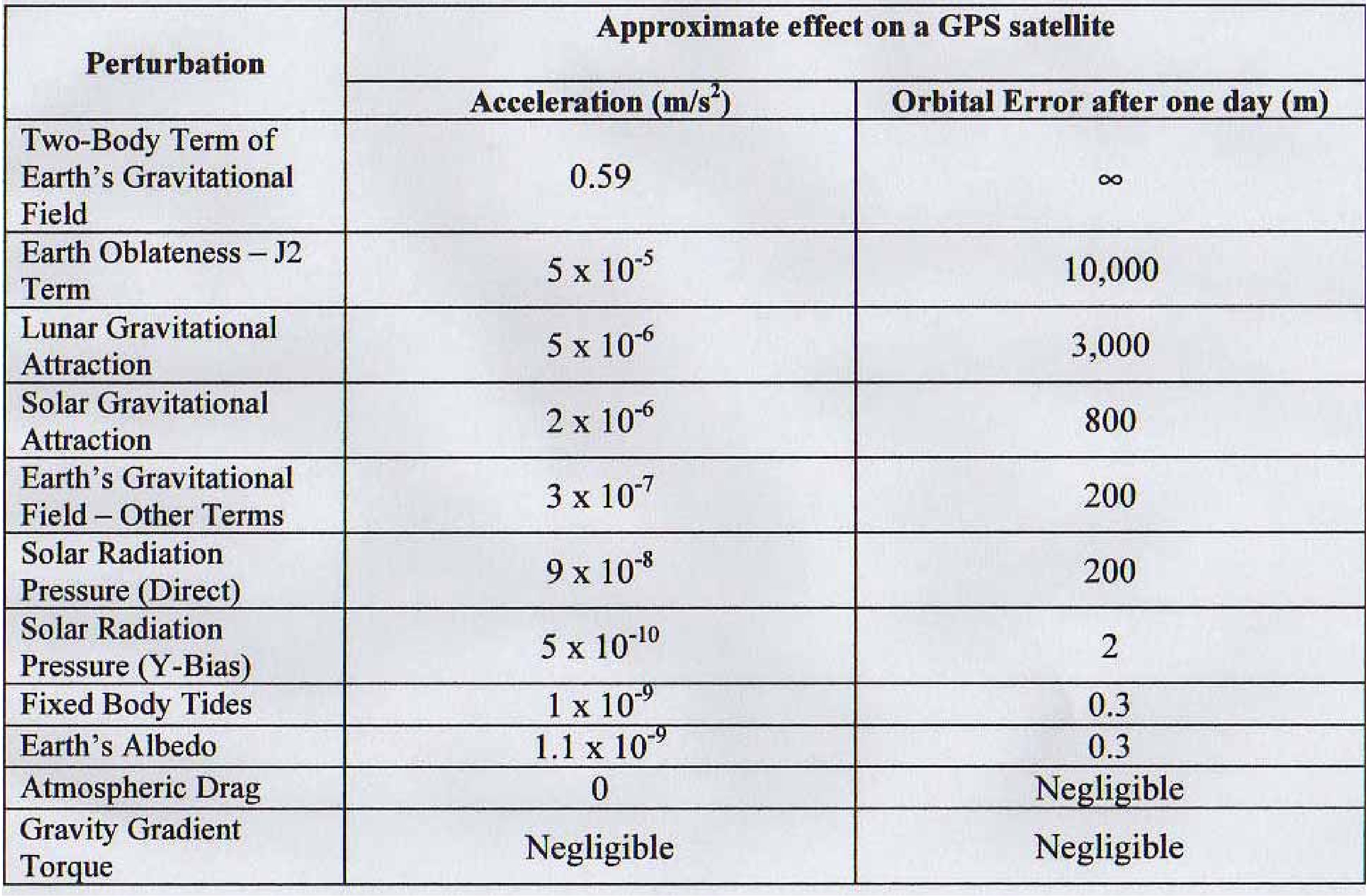
Geocentric Coordinates of IGS Tracking Stations (>130 sites)					
Final positions	horizontal	3 mm	12 days	weekly	weekly
	vertical	6 mm			
Final velocities	horizontal	2 mm/yr	12 days	weekly	weekly
	vertical	3 mm/yr			
Earth Rotation Parameters: **Polar Motion (PM)** **Polar Motion Rates (PM rate)** **Length-of-day (LOD)**					
Ultra-Rapid (predicted half)	PM	0.3 mas	real time	four times daily	four times daily (00,06,12,18 UTC)
	PM rate	0.5 mas/day			
	LOD	0.06 ms			
Ultra-Rapid (observed half)	PM	0.1 mas	3 hours	four times daily	four times daily (00,06,12,18 UTC)
	PM rate	0.3 mas/day			
	LOD	0.03 ms			
Rapid	PM	<0.1 mas	17 hours	daily	daily (12 UTC)
	PM rate	<0.2 mas/day			
	LOD	0.03 ms			
Final	PM	0.05 mas	~13 days	weekly	daily (12 UTC)
	PM rate	<0.2 mas/day			
	LOD	0.02 ms			

International GPS Service (IGS) Forecast Precise Ephemerides



Atmospheric Parameters				
Final tropospheric zenith path delay	4 mm	< 4 weeks	weekly	2 hours
Ultra-Rapid tropospheric zenith path delay	6 mm	2-3 hours	every 3 hours	1 hour
Final Ionospheric TEC grid	2-8 TECU	~11 days	weekly	2 hours; 5 deg (lon) x 2.5 deg (lat)
Rapid Ionospheric TEC grid	2-9 TECU	<24 hours	daily	2 hours; 5 deg (lon) x 2.5 deg (lat)

Predictable Sources of Orbital Perturbation



Perturbation	Approximate effect on a GPS satellite	
	Acceleration (m/s^2)	Orbital Error after one day (m)
Two-Body Term of Earth's Gravitational Field	0.59	∞
Earth Oblateness – J2 Term	5×10^{-5}	10,000
Lunar Gravitational Attraction	5×10^{-6}	3,000
Solar Gravitational Attraction	2×10^{-6}	800
Earth's Gravitational Field – Other Terms	3×10^{-7}	200
Solar Radiation Pressure (Direct)	9×10^{-8}	200
Solar Radiation Pressure (Y-Bias)	5×10^{-10}	2
Fixed Body Tides	1×10^{-9}	0.3
Earth's Albedo	1.1×10^{-9}	0.3
Atmospheric Drag	0	Negligible
Gravity Gradient Torque	Negligible	Negligible

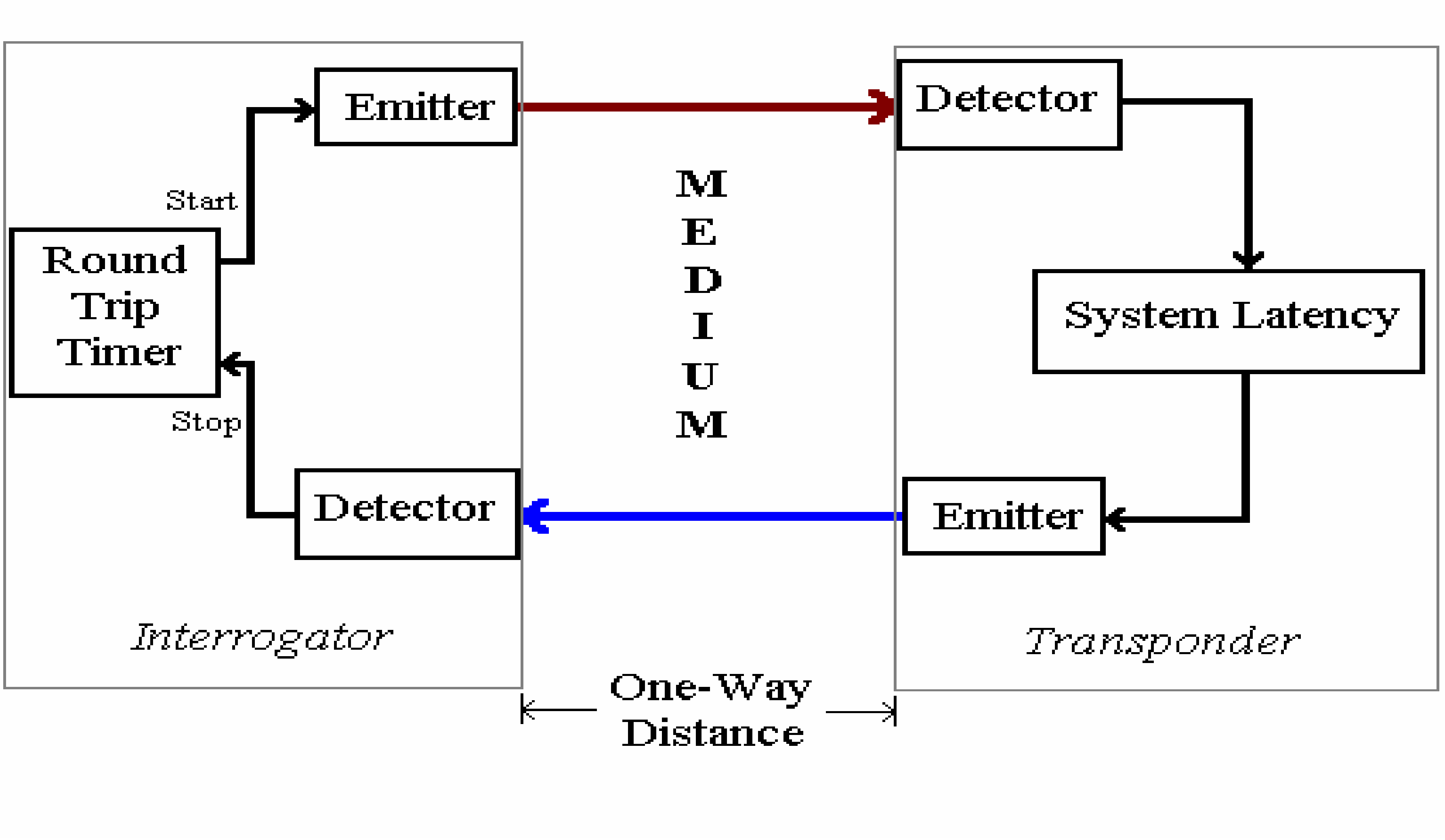
Unpredictable Sources of Orbital Perturbation

Aerodynamic Drag from Particles in the Van Allen Belt

“Space Weather”

Ionospheric Effects

Transponder Determination of GPS Satellite Position



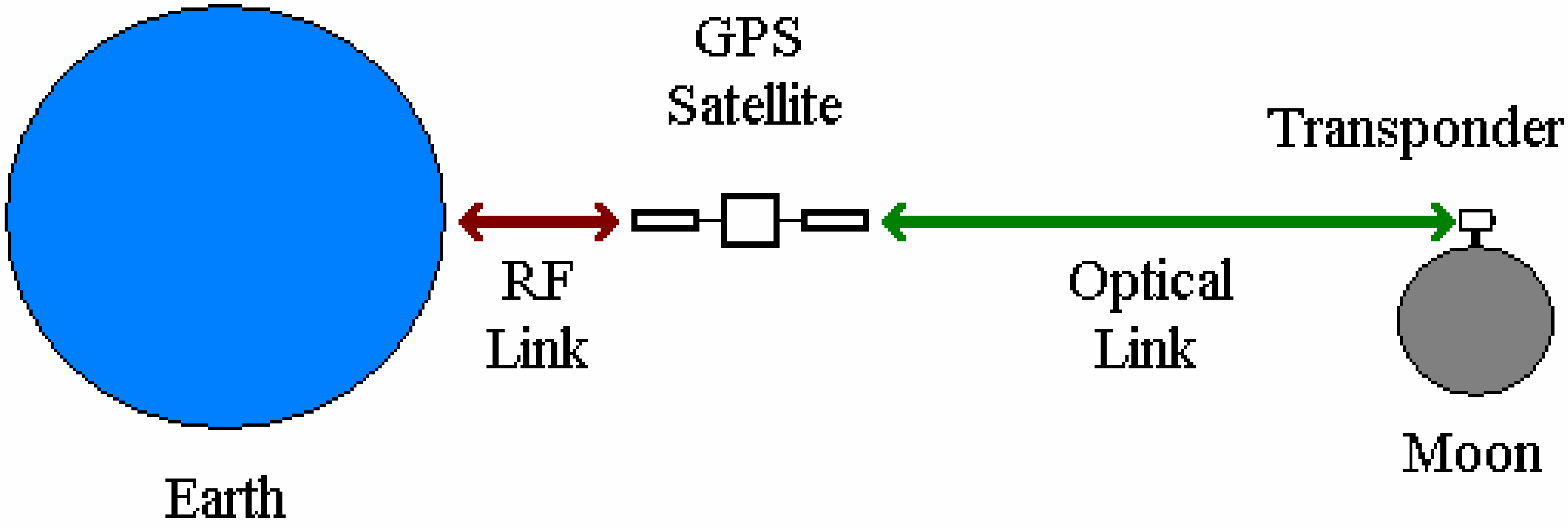
Advantages of a Lunar Transponder

Exo-Atmospheric Signal Propagation

Lunar Ephemeris is Well-Known

Orbit not measurably affected by Solar Wind and Solar Radiation

Synchronous Orbit – reduces number of Transponders always facing Earth


GPS
Satellite
Transponder
RF
Link
Optical
Link
Moon
Earth

Transponder Link:
Optical vs. RF

Short wavelength of Optical Links provides
Higher Bandwidth over RF Links

Gain for a given Aperture Scales with
Inverse Square of Wavelength

Transponder Link: Optical vs RF

$$G = 10 \log_{10} (\pi D / \lambda)^2$$

G = Gain in dBi

D = aperture Diameter

λ = wavelength

Comparison of Aperture Gains

25 cm (10 inch) Aperture at 830 nm

≈ 120 dBi

10 meter (33 feet) Aperture at 2.54 GHz

≈ 50 dBi

Implications for System Design

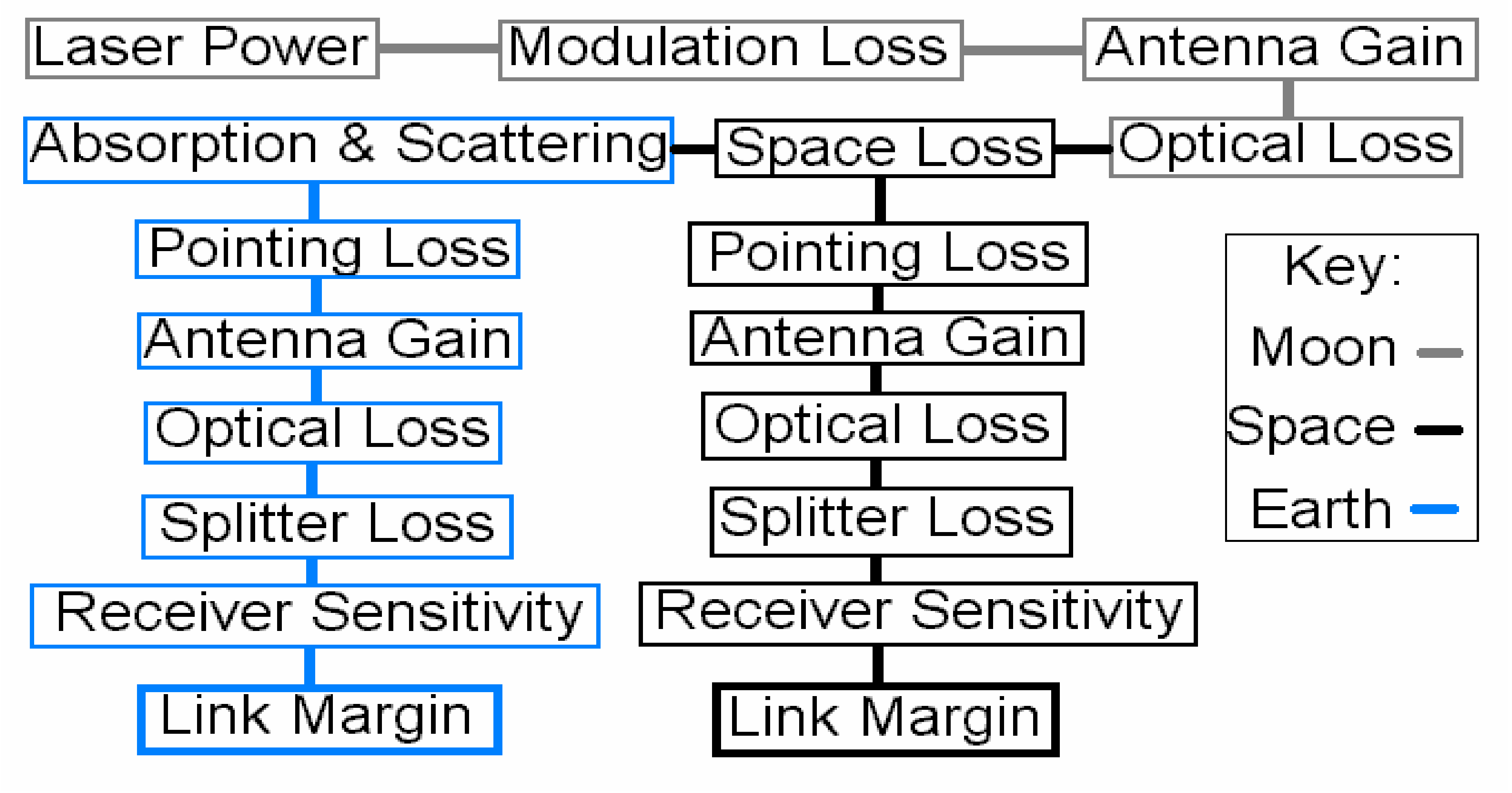
Reduced Component Size as compared to
Electronic Counterparts

Ability to Concentrate Power in Narrow Beams

Reduction in Transmitted Power Requirements

Overall Payload Size/Mass Reduction

Link Budget Block Diagram



Link Budget Calculation

Transmitter Power, 1 W @ 830 nm	0 dBW
Transmitter Antenna Gain, 1 m Dia.	131.6 dBi
Transmitter Optical Losses	- 6.0 dB
Space Propagation Losses	-315.3 dB
Losses in Vacuum	0 dB
Spatial Pointing Losses	- 1.0 dB
Receiver Antenna Gain, 1 m Dia.	131.6 dBi
Receiver Optical Losses	- 6.0 dB
Spatial Tracking Splitter Losses	- 1.0 dB
Receiver Sensitivity	84.0 dBW
Link Margin	**17.9 dB**

Assume: 100 Mbps, 10-6 BER

Various Aperture Gains Expressed in dBi

Aperture	**Gain**
10 cm	111.6 dBi
0.5 m	125.5 dBi
1.0 m	131.6 dBi
1.5 m	135.1 dBi

Aperture Tradeoff Considerations

Every pound saved from Payload to LEO
saves 200-250 pounds in Launch Vehicle weight

Every pound saved from Lunar Landing Payload
saves ~ 1000 pounds in Launch Vehicle weight

Various Laser Powers Expressed in dBW

Laser Power	dB Value
100 mW	- 10 dBW
500 mW	- 3 dBW
1.0 W	0 dBW
2.0 W	3 dBW

Moon - to - Earth Distances and Associated Propagation Losses

Minimum: 364,800 km
(Propagation Loss = - 314.8 dB)

Nominal: 384,00 km
(Propagation Loss = - 315.3 dB)

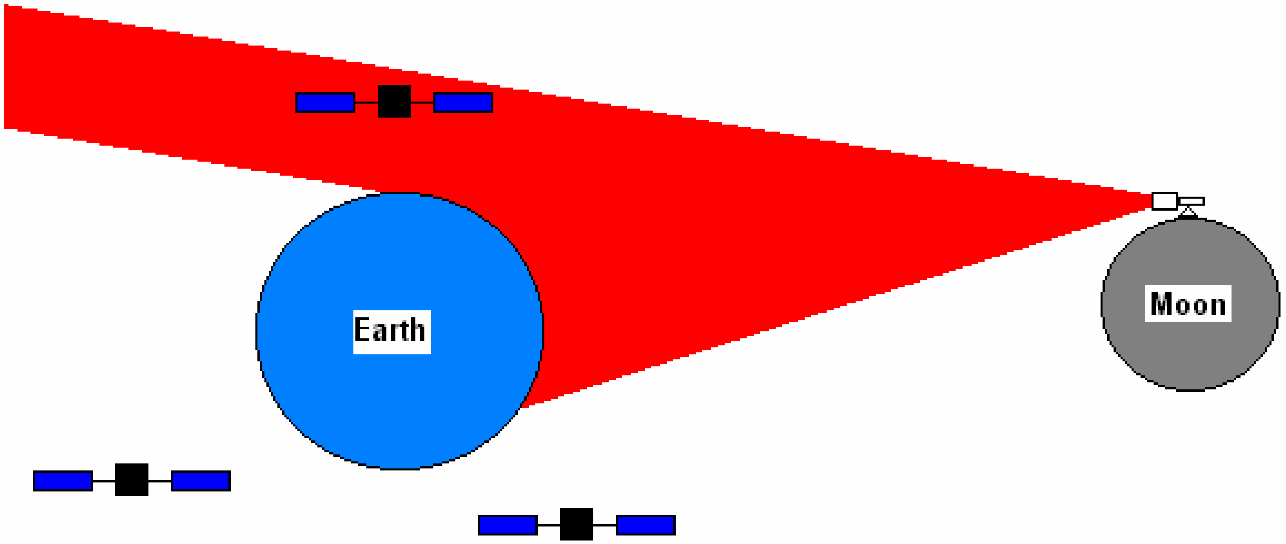
Maximum: 403,200
(Propagation Loss = - 315.7 dB)

Associated Beam Diameters

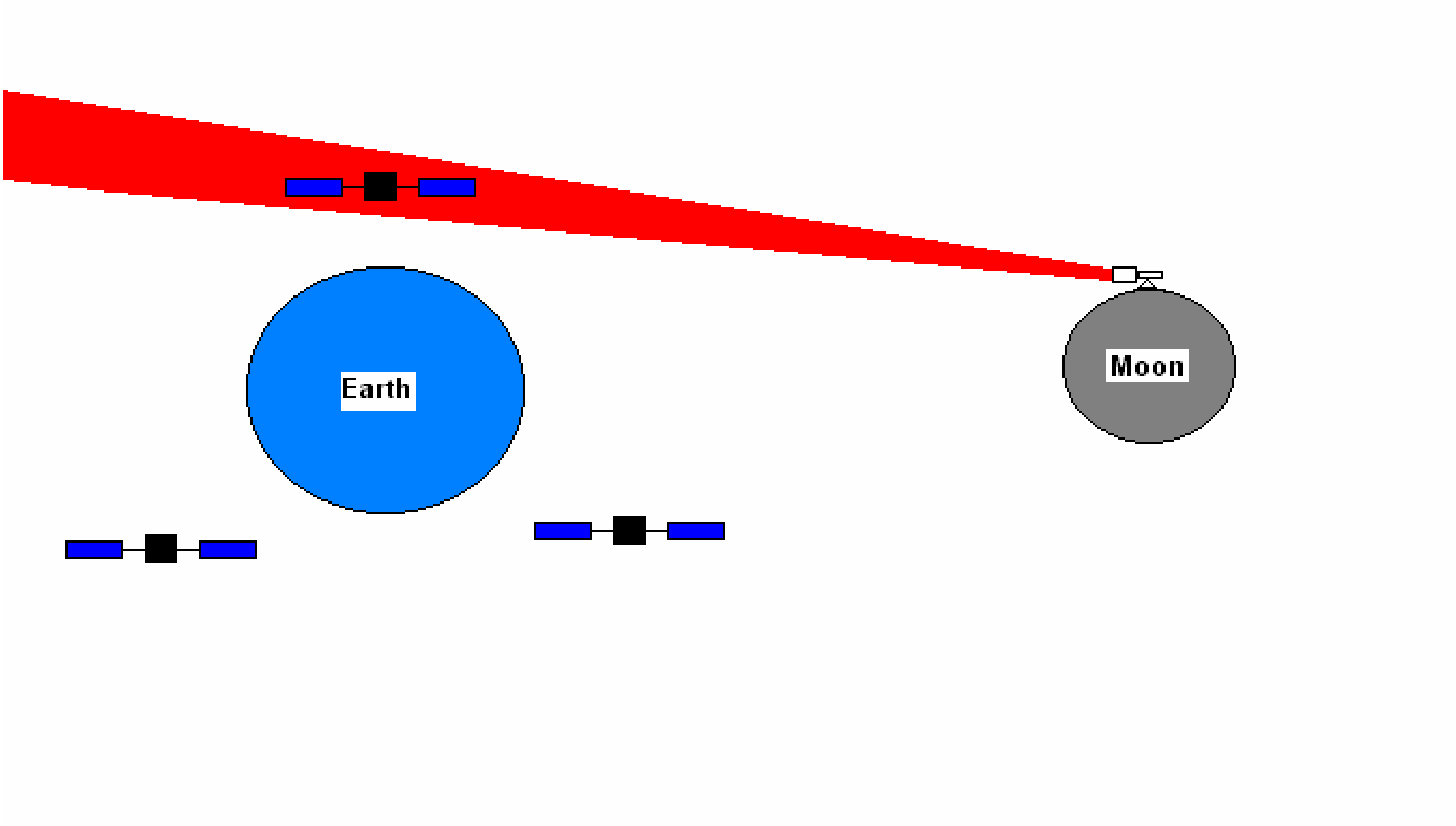
Assume:
1 meter Aperture on the Moon
830 nm Wavelength

Diffraction-Limited Beam Diameter Near Earth
303 meters (364,800 km)
335 meters (403,200 km)

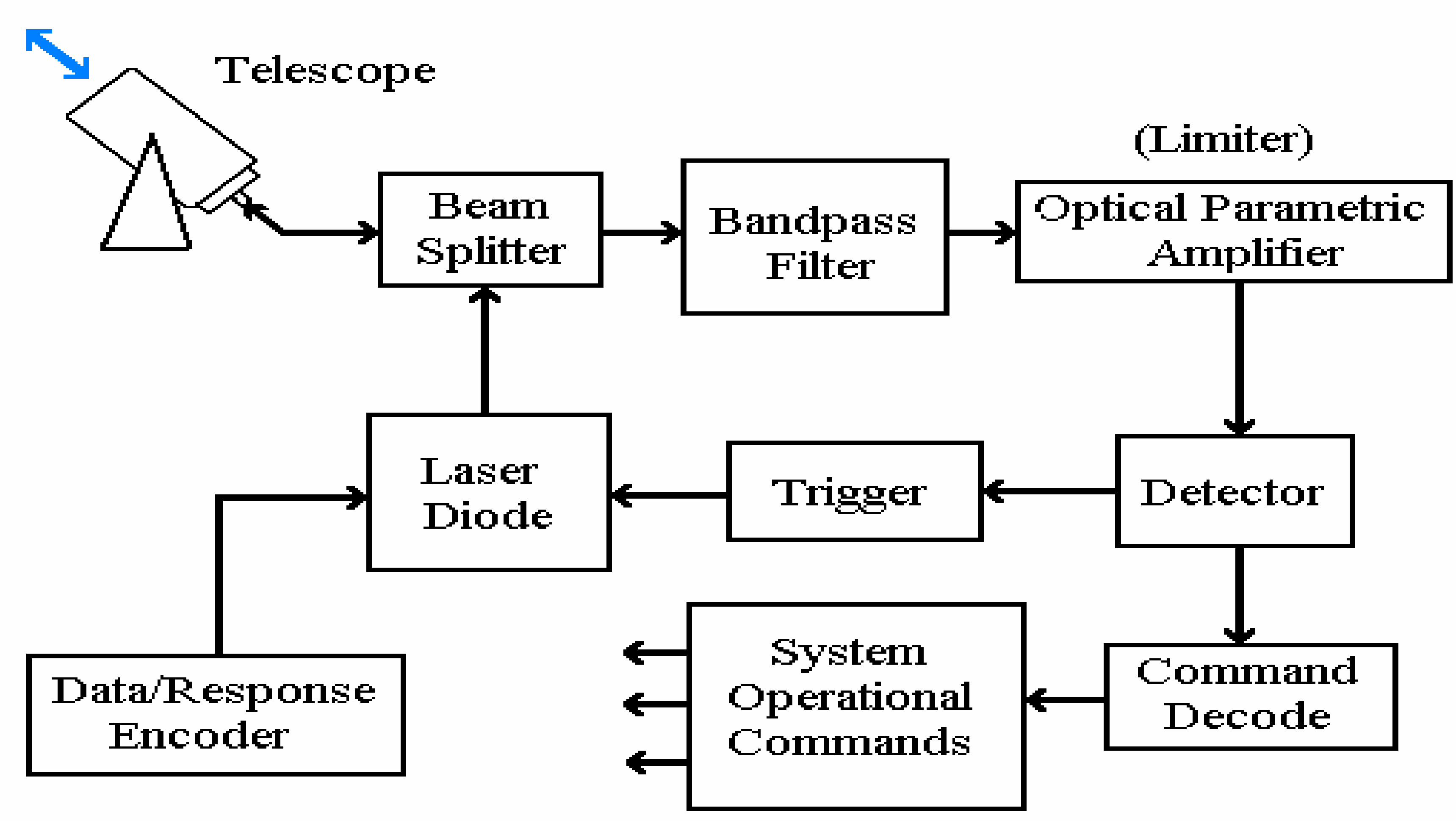
Enhanced Satellite Detection by Increasing Beam Divergence



Link Margin is Maximized by Narrowing Beam Divergence once Lock-In Occurs



Lunar Transponder Block Diagram



Thermal Considerations

Lunar Daytime

No Surface Contact

Solar Irradiation ~ 1400 W/m^2

Direct + Indirect (surface reflections)

Absorptivity – dependent

May be compromised by dust contamination

Thermal Considerations - continued

Lunar Daytime

Surface Contact

Local Albedo - dependent

Surface Temperatures ~ 123ºC max.

Lunar Soil Thermal Conductivity:

1.72 to 2.95 X 10^{-2} W/m K

Thermal Considerations - continued

Lunar Darkness

Surface Temperatures as low as
-233ºC (40 K)

Lasts for ~ 2 weeks

Thermal Considerations - continued

Radiative Loss Example

Assume a cube 1m on a side, sitting on the Moon with emissivity of 0.9 and surface temp. = 20ºC

$$Q = \varepsilon \sigma A T^4$$

$$= 0.9 \text{ X } 5.67 \text{ X } 10^{-8} \text{ W/m}^2\text{K}^4 \text{ X } 5\text{m}^2 \text{ X } (293\text{K})^4$$

$$= 1880.5 \text{ Watts}$$

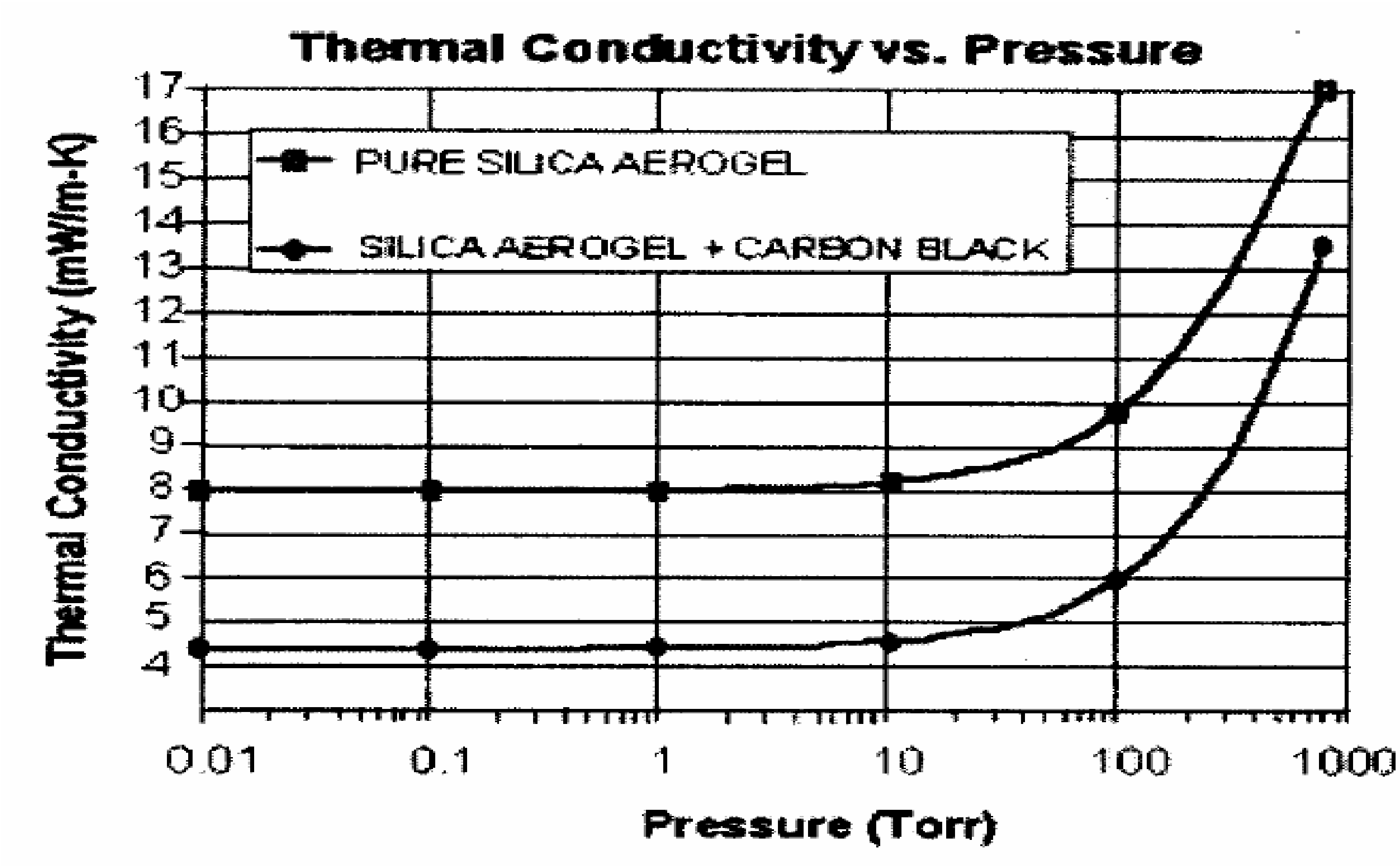
Radiative Loss Example - continued

To maintain 1880.5 Watts for 2 weeks
(336 hours)

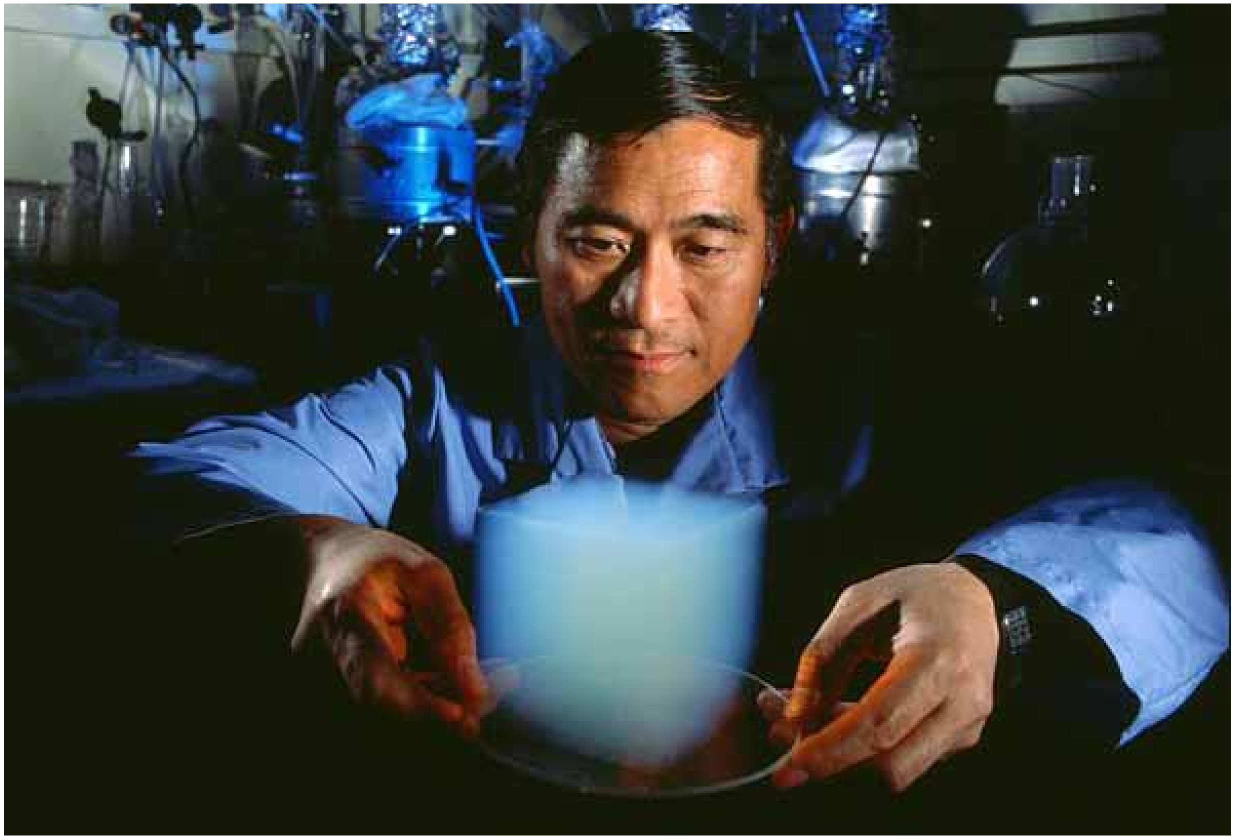
= 631.8 kWhr

Radiative Loss Example - continued

High Performance Insulation



Paul and Diller, 2003



NASA / JPL, 2006

Radiative Loss Example - continued

$$Q = k A (dT/dx)$$

using:

$k = 0.0045$ W/m-K

$A = 5$ m^2

$dT = 253$ K (293 K - 40 K)

$dx = 0.01$ m, 0.1 m

Radiative Loss Example - continued

For 1 cm thick Aerogel insulation:

~ 570 Watts, ~ 191.5 kWhr

For 10 cm thick Aerogel insulation:

~ 57 Watts, ~ 19.2 kWhr

Importance of Thermal Leaks

Radiative Loss Example - continued

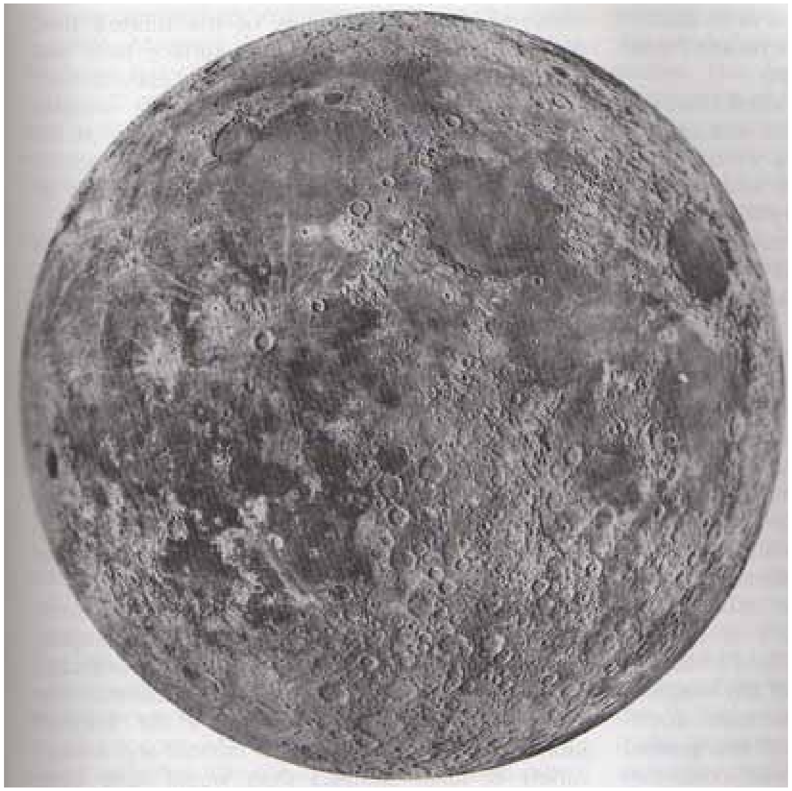
Segregation by Temperature Sensitivity

Optical Components and Support
- Low Coefficient of Thermal Expansion Materials

Electronics - Highest Thermal Sensitivity

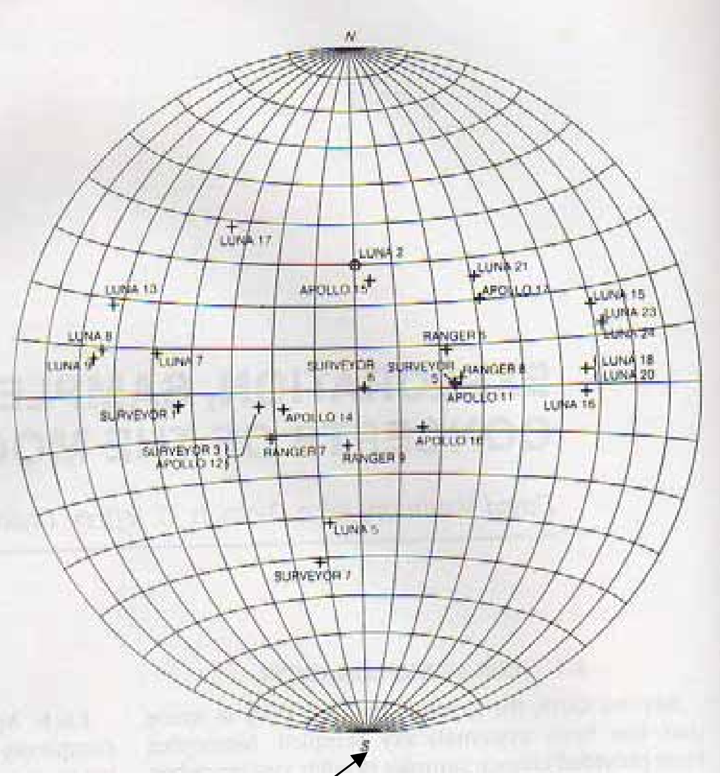
Batteries - Reduced Thermal Sensitivity

Location of Transponders on the Moon



Heiken, et al., 1993

Location of Transponders on the Moon



Equatorial Diametric Locations

Equatorial Diametric Locations

Polar Location

Heiken, et al., 1993

Conclusions

GPS Accuracy can be Improved
using Lunar Transponders

Freedom from Influence of Unpredictable
Atmospheric and Solar Effects

Cost/Benefit should be considered
in light of Larger Mission Objectives

Acknowledgements

Salute taikonaut and spacewalker Zhai Zhigang,

who, in the spirit of Captain Nemo

Acknowledgements

Bravely defends his ship against attack

Acknowledgements

Reuters, 2008

from a Giant Space Octopus