Frequency-Dependent Design Considerations for Alternative PNT Systems

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Overview

- Frequency selection for Alternative PNT system
- Definitions
- Discussion of ITU reports, models
- Timing Impacts

Definitions

Radar-frequency bands according to IEEE standard

L, S, C, Ku… bands

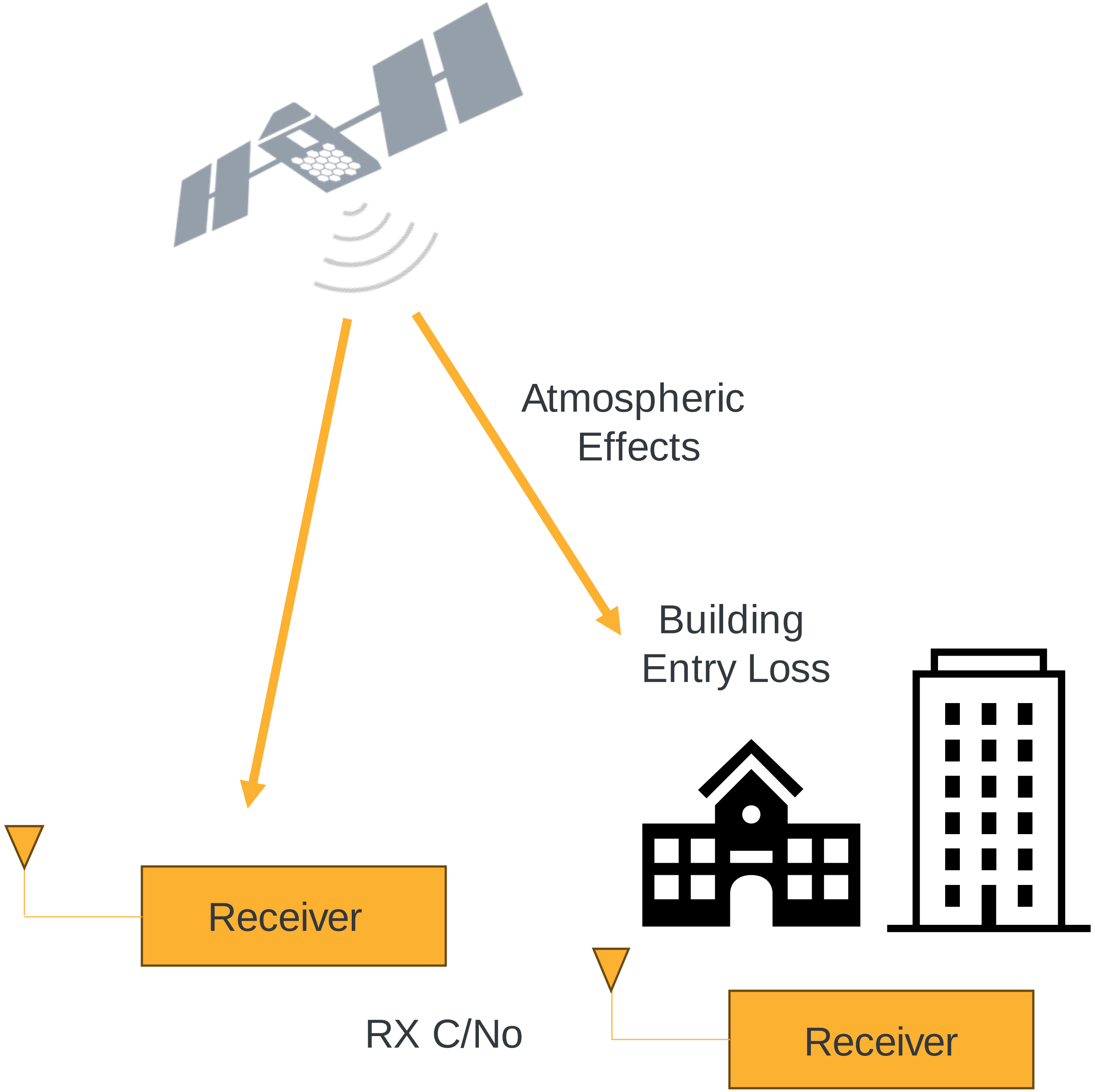
Band designation	Frequency Range	Explanation
UHF	0.3 to 1 GHz	Ultra-high frequency
L	1 to 2 GHz	Long wave
S	2 to 4 GHz	Short wave
C	4 to 8 GHz	Compromise between S and X
X	8 to 12 GHz	Used in World War II for fire control, X for cross (as in crosshair). Exotic.
K_u	12 to 18 GHz	*Kurz*-under
K	18 to 27 GHz	German: *Kurz* (short)
K_a	27 to 40 GHz	*Kurz*-above

521-2002 - IEEE Standard Letter Designations for Radar-Frequency Bands

Definitions

Link Budget Considerations

1. Attenuation Sources
   - Free Space Path Loss
   - Absorption Loss
     - Ionospheric
     - Atmospheric
     - Rain/Clouds
   - Building Entry Loss
2. Transmit EIRP
3. Antenna Pattern
4. Receiver Noise Figure



Definitions

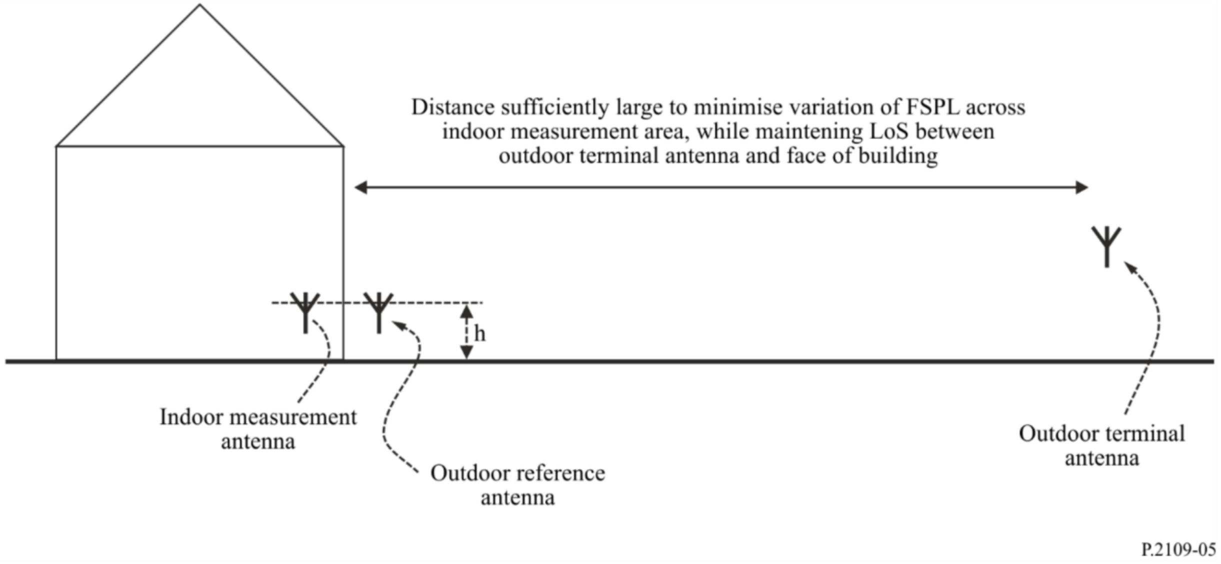
Building Entry Loss (BEL)

“Building entry loss is the additional loss due to a terminal being inside a building”

“Building entry loss can be measured as the difference, expressed in dB, between the spatial median of the signal level outside the illuminated face of a building and the spatial median of the signal level inside the building at the same height above ground.”

FIGURE 5

Location of reference and measurement antennas for building entry loss measurement



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Compilation of measurement data relating to building entry loss
Report ITU-R P.2346-3

Effects of building materials and structures on radio wave propagation above about 100 MHz
Recommendation ITU-R P.2040-3 (08/2023)

Prediction of building entry loss
Recommendation ITU-R P.2109-2 (8/2023)

Testing Campaign ITU-R P.2346-3

Compilation of measurement data relating to building entry loss

- Global test campaign with nearly 40 sites collecting BEL data
- Testing from 88MHz to over 32GHz
- Commercial and Residential test locations
- Typical building materials tested in the study
  - glass, concrete, brick, wood, plasterboard
  - typically energy efficient glass (metal coated) separately studied
- Various slant-path measurement conditions were tested.
  - Parking lot
  - Helicopter
  - Fixed Towers (Satellite simulation)

Report ITU-R P.2346-3 (05/2019)
https://www.itu.int/dms_pub/itu-r/opb/rep/R-REP-P.2346-3-2019-PDF-E.pdf

BEL measurements for two office buildings in the frequency range 800 MHz-28 GHz

TABLE 57

Summary of building compositions.

Façade elements	Traditional building (STV)	Modern Building (AAU)
Wall	10 cm thick made of light concrete and brick.	45 cm thick multi-layer composed of reinforced-concrete, brick and other isolation layers
Windows	Single-layered clear glass windows with wooden frames.	2-layered energy-efficient (metal-coated) windows with metal frame

FIGURE 171

Traditional office building (STV)

FIGURE 172

Modern office building (AAU)

FIGURE 173

Overview of the measurement positions (grey: outdoor reference, green: indoor, orange: intermediate corridor, red: deep indoor)

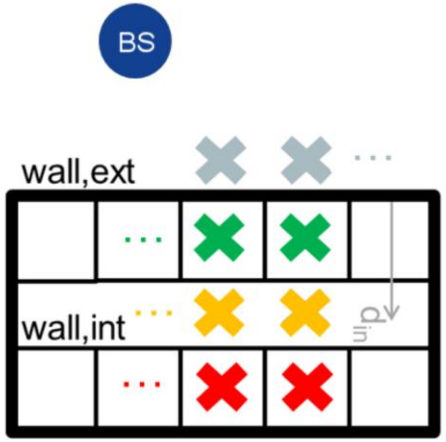

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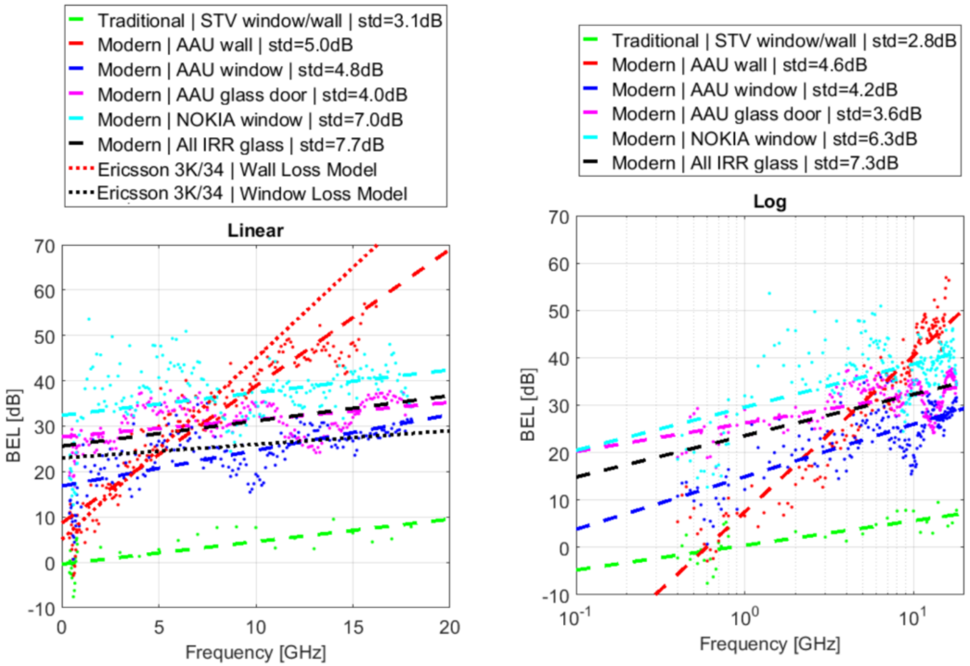
TABLE 58

Summary of BEL values for the two office buildings considering all indoor measurement positions

	Traditional Office Building		Modern Office Building	
Frequency	**Mean**	**STD**	**Mean**	**STD**
800 MHz	14.3	5.4	21.8	5.4
2 GHz	14.7	7.1	25.9	5.9
3.5 GHz	17.8	7.4	28.9	6.3
5.2 GHz	17.7	6.0	37.0	6.9
10 GHz	22.3	7.9	39.1	6.5
18 GHz	21.9	8.9	49.9	6.8
28 GHz	26.4	9.5	39.0*	3.9*

FIGURE 176

Normal incidence attenuation measurement results and associated linear models for the frequency range 400 MHz - 18 GHz, considering the frequency in linear scale (a) and logarithmic scale (b)



Report ITU-R P.2346-3 (05/2019)

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Materials Study ITU-R P.2040-3 (08/2023)

Effects of building materials and structures on radio wave propagation above about 100 MHz

TABLE 3

Material properties

Material class	**Real part of relative permittivity**		**Conductivity S/m**		**Frequency range**
	a	*b*	*c*	*d*	GHz
Vacuum (≈ air)	1	0	0	0	0.001-100
Concrete	5.24	0	0.0462	0.7822	1-100
Brick	3.91	0	0.0238	0.16	1-40
Plasterboard	2.73	0	0.0085	0.9395	1-100
Wood	1.99	0	0.0047	1.0718	0.001-100
Glass	6.31	0	0.0036	1.3394	0.1-100
Glass	5.79	0	0.0004	1.658	220-450
Ceiling board	1.48	0	0.0011	1.0750	1-100
Ceiling board	1.52	0	0.0029	1.029	220-450
Chipboard	2.58	0	0.0217	0.7800	1-100
Plywood	2.71	0	0.33	0	1-40
Marble	7.074	0	0.0055	0.9262	1-60
Floorboard	3.66	0	0.0044	1.3515	50-100
Metal	1	0	10^7	0	1-100
Very dry ground	3	0	0.00015	2.52	1-10 only
Medium dry ground	15	−0.1	0.035	1.63	1-10 only
Wet ground	30	−0.4	0.15	1.30	1-10 only

FIGURE 1

Reflection and refraction of plane waves at plane interface

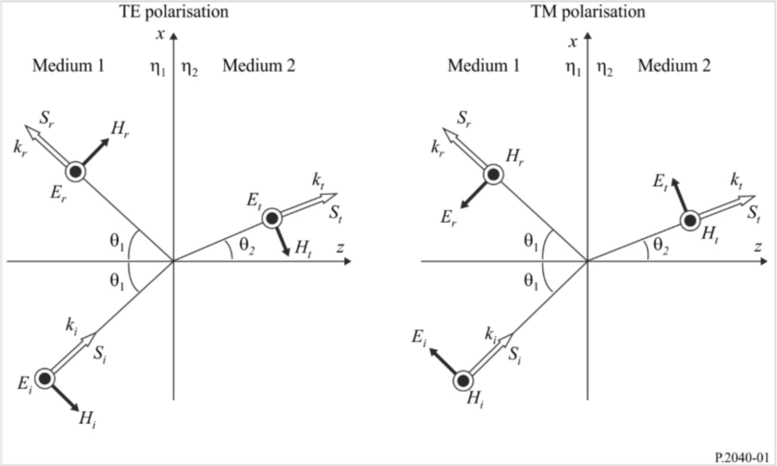
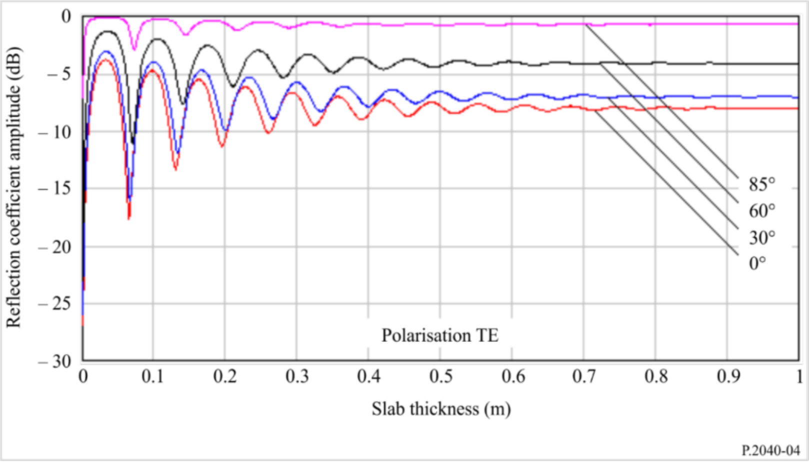


FIGURE 4

Reflection coefficient for a concrete slab at 1 GHz, TE polarisation



Recommendation ITU-R P.2040-3 (08/2023)
https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.2040-3-202308-I!!PDF-E.pdf

Prediction of building entry loss ITU-R P.2109-2

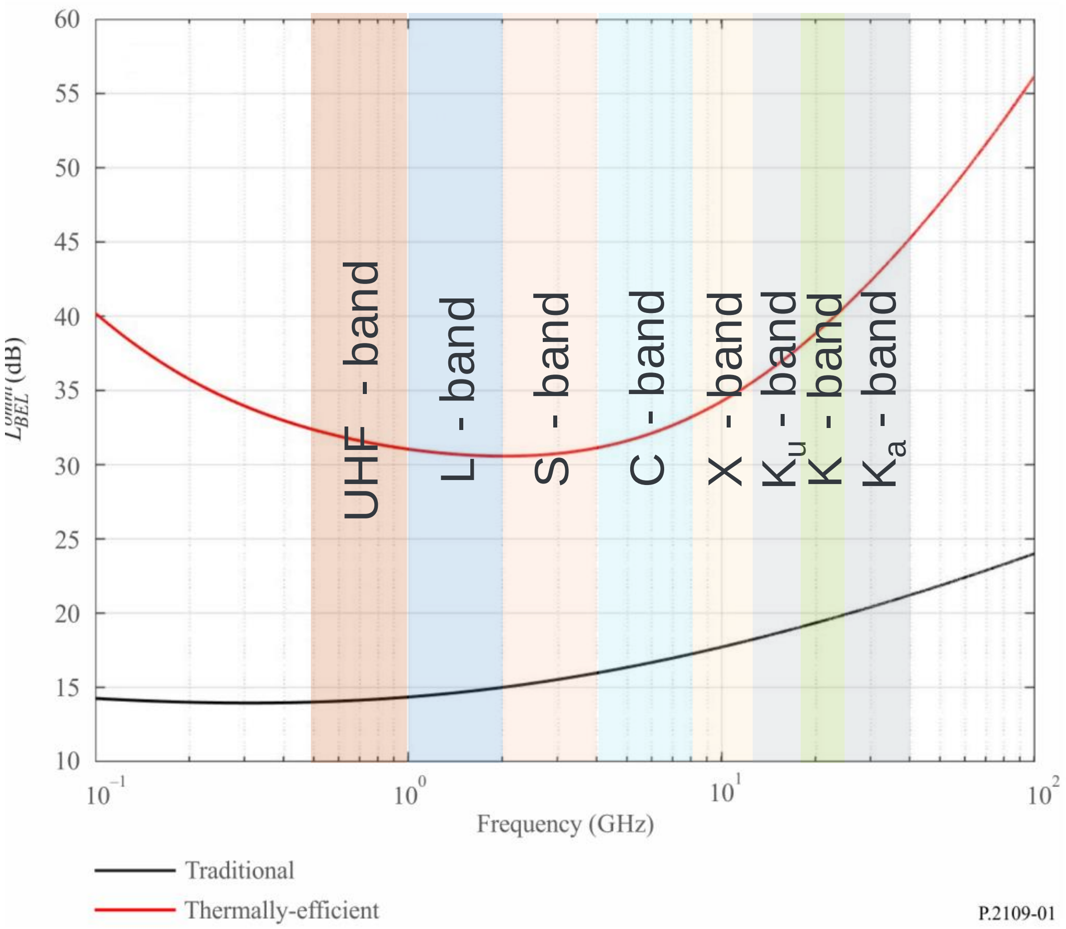
Model was developed with empirical data from ITU-R P.2346, and ITU-R P.2040

Traditional vs Modern building construction

“Typically, the presence of metallised glass windows, insulated cavity walls, thick reinforced concrete and metal foil back cladding is a good indication of a thermally-efficient building.”

FIGURE 1

Median building entry loss predicted at horizontal incidence



P.2109-01

Recommendation ITU-R P.2109-2 (08/2023)
https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.2109-2-202308-I!!PDF-E.pdf

Atmospheric effects - ITU-R P.618-11

Propagation data and prediction methods required for the design of Earth-space telecommunication systems

- Ionospheric effects
- Propagation delay
- Absorption
- Dispersion (ps/Hz)

TABLE 1

Estimated* ionospheric effects for elevation angles of about 30° one-way traversal**
(derived from Recommendation ITU-R P.531)

Effect	Frequency dependence	0.1 GHz	0.25 GHz	0.5 GHz	1 GHz	3 GHz	10 GHz
Faraday rotation	$1/f^2$	30 rotations	4.8 rotations	1.2 rotations	108°	12°	1.1°
Propagation delay	$1/f^2$	25 µs	4 µs	1 µs	0.25 µs	0.028 µs	0.0025 µs
Refraction	$1/f^2$	< 1°	< 0.16°	< 2.4′	< 0.6′	< 4.2″	< 0.36″
Variation in the direction of arrival (r.m.s.)	$1/f^2$	20′	3.2′	48″	12″	1.32″	0.12″
Absorption (auroral and/or polar cap)	$\approx 1/f^2$	5 dB	0.8 dB	0.2 dB	0.05 dB	6×10^{-3} dB	5×10^{-4} dB
Absorption (mid-latitude)	$1/f^2$	< 1 dB	< 0.16 dB	< 0.04 dB	< 0.01 dB	< 0.001 dB	$< 1 \times 10^{-4}$ dB
Dispersion	$1/f^3$	0.4 ps/Hz	0.026 ps/Hz	0.0032 ps/Hz	0.0004 ps/Hz	1.5×10^{-5} ps/Hz	4×10^{-7} ps/Hz
Scintillation(1)	See Rec. ITU-R P.531	See Rec. ITU-R P.531	See Rec. ITU-R P.531	See Rec. ITU-R P.531	> 20 dB peak-to-peak	≈ 10 dB peak-to-peak	≈ 4 dB peak-to-peak

* This estimate is based on a TEC of 10^{18} electrons/m², which is a high value of TEC encountered at low latitudes in daytime with high solar activity.

** Ionospheric effects above 10 GHz are negligible.

(1) Values observed near the geomagnetic equator during the early night-time hours (local time) at equinox under conditions of high sunspot number.

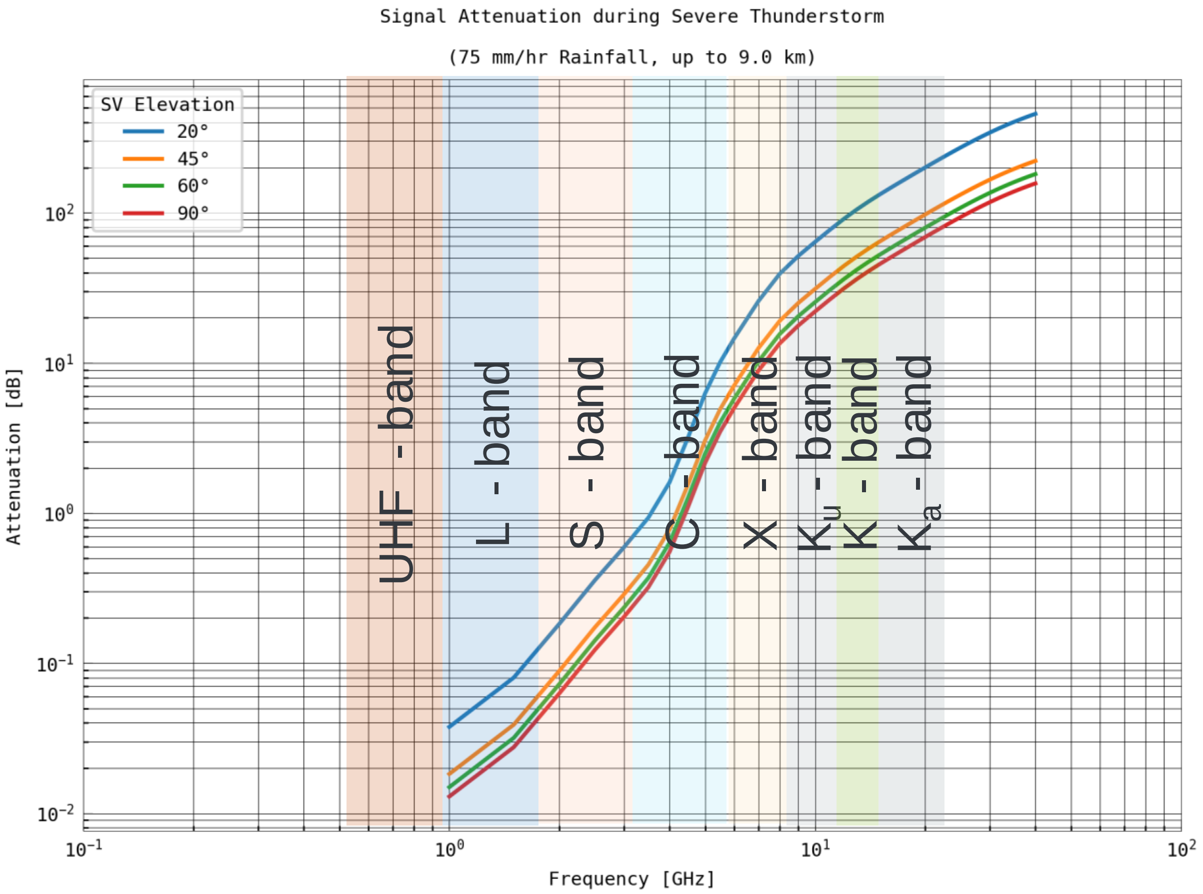
Recommendation ITU-R P.618-11 (09/2013)
https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.618-11-201309-S!!PDF-E.pdf

Atmospheric effects - ITU-R P.618-11

Propagation data and prediction methods required for the design of Earth-space telecommunication systems

Propagation losses

- Attenuation by Rain, atmospheric gases
- Rain fade propagation loss plot developed using ITU ITU-R P.838-3 Model
- Conditions assumed to be thunderstorm in Florida



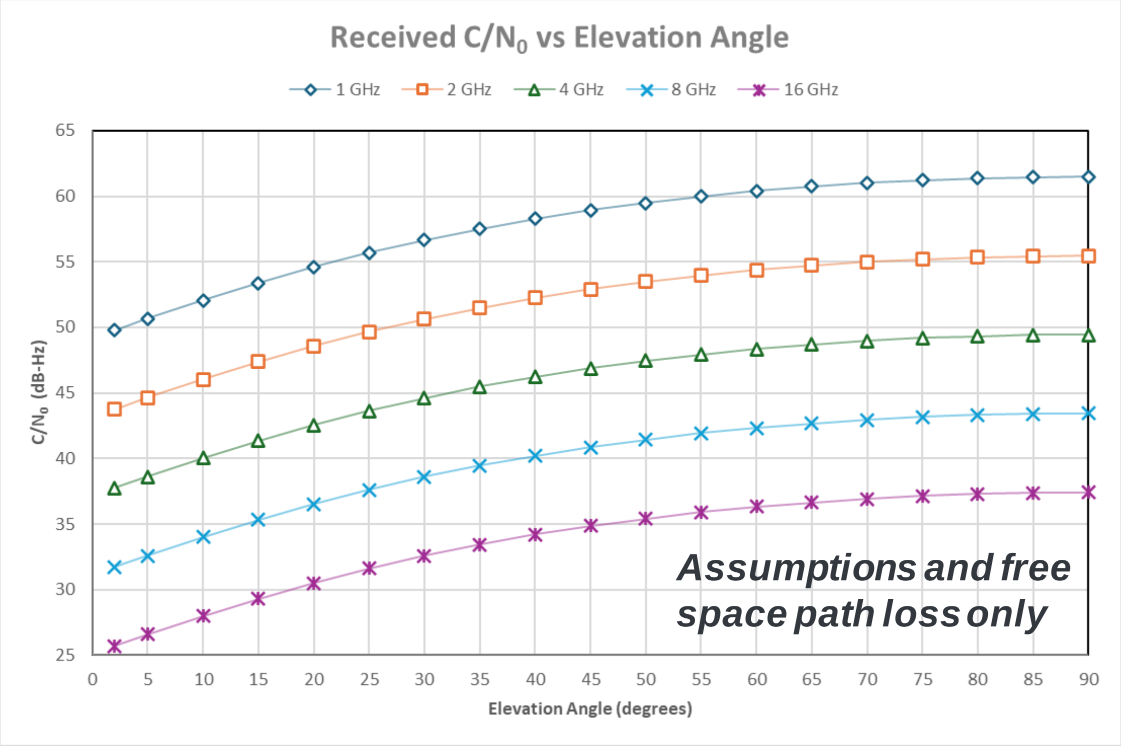
Recommendation ITU-R P.618-11 (09/2013)
https://www.itu.int/dms_pubrec/itu-r/rec/p/R-REC-P.618-11-201309-S!!PDF-E.pdf

Link Budget Analysis

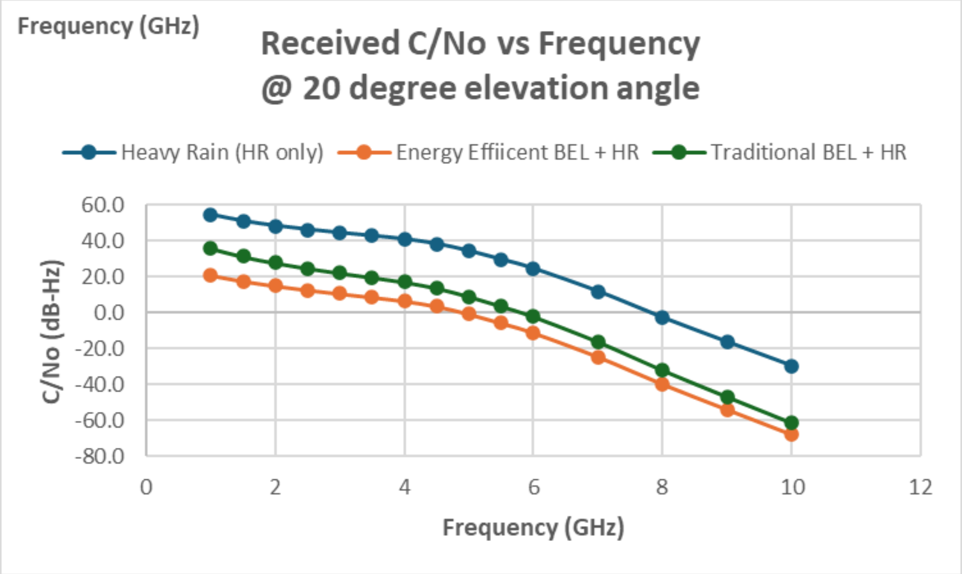
Link budget estimating line-of-sight received signal quality as a function of frequency given consistent transmitter/receiver properties

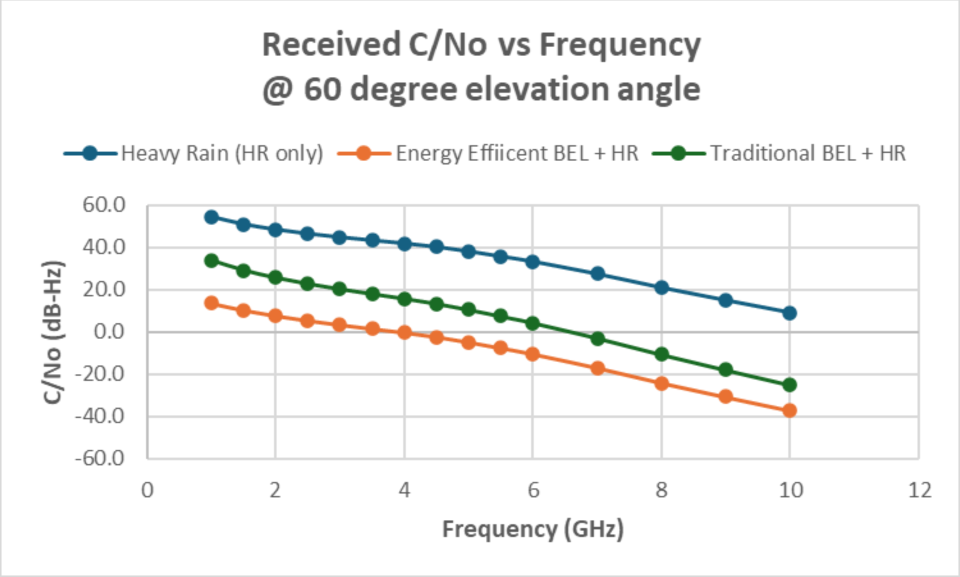
Assumptions (consistent at each frequency)

- Orbit Altitude: 800 km
- Transmit EIRP: 10 Watts
- Receiver Antenna: 0 dBi
- Receiver Noise Figure: 2 dB
- Receiver Thermal Noise Density: -204 dBW / m^2



Link budget including heavy rain and BEL models





Timing Impacts: Pseudorange Measurement Error Bound

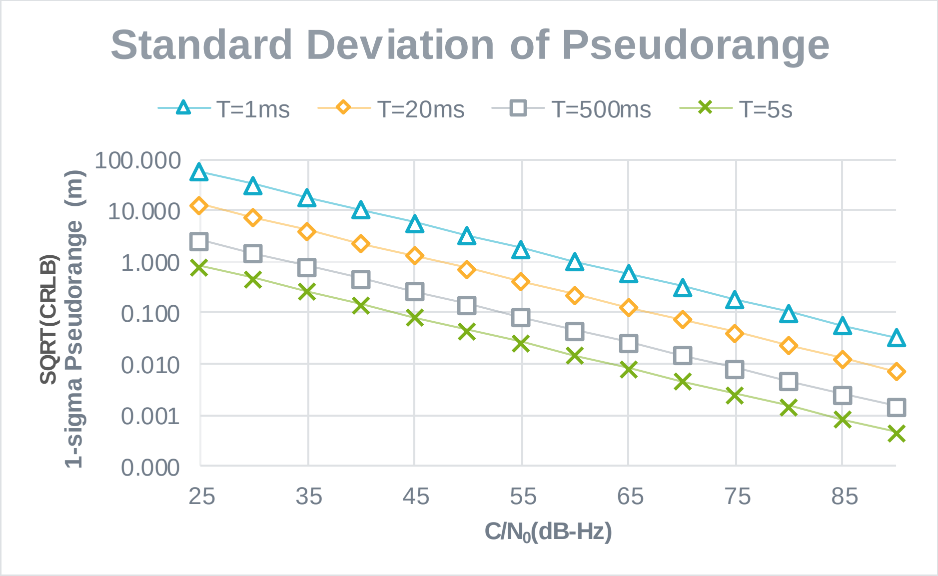
Standard deviation of timing measurement error in additive white gaussian noise, $\sigma_{\tau_{ML}}$, assuming code-based pseudoranging which can be achieved is a function of:

- Signal quality (i.e., carrier-to-noise density, C/No);
- Signal Bandwidth (W);
- Signal Integration Time (T).

$$\sigma_{\tau_{ML}} = \frac{3.444 * 10^{-4}}{\sqrt{\frac{C}{N_0} WT}}$$

Additional errors in pseudorange from satellite clock, ephemeris, relativistic, atmospheric effects, ionospheric effects, tropospheric effects, multipath, and equipment error sources.

Takeaway: Performance degrades as a function of signal quality (SNR) and waveform design



*Assume 1 MHz code bandwidth

[1] Grewal, M. S., Weill, L. R., & Andrews, A. P. (2007). *Global positioning systems, inertial navigation, and integration* (2nd ed.)

Timing Impacts: PNT Solution Error Bound

The Best Linear Unbiased Minimum-Variance Estimator (BLUE) for a GNSS solution is found by Weighted Least Squares (WLS)

- Requiring 4 or more satellite pseudorange measurements, each with their own independent ranging error

A typical four state WLS solution consists of

- x: Receiver state vector (example state consists of 3 position and 1 clock)
- H: Linearization of pseudorange equation around current state (i.e., the Jacobian relating changes in state vector to changes in pseudorange measurements)
  - a_i: Unit vector between linearization point and the i^th satellite position
- p: Pseudorange measurement vector with gaussian errors
- R: Covariance matrix of the ranging measurements
- Δp: Pseudorange residuals
- Δx: State update vector
- dx: Error in state update vector
- dp: Error in pseudorange residuals

Takeaway: PNT Solution accuracy is dependent on two primary factors

- Satellite geometry (expressed in the covariance estimates H matrix)
- Ranging accuracy (expressed in the covariance estimates R matrix)

$$H = \begin{bmatrix} a_{x1} & a_{y1} & a_{z1} & 1 \\ a_{x2} & a_{y2} & a_{z2} & 1 \\ \vdots & \vdots & \vdots & \vdots \\ a_{x(N-1)} & a_{y(N-1)} & a_{z(N-1)} & 1 \\ a_{xN} & a_{yN} & a_{zN} & 1 \end{bmatrix}$$

WLS Solution

$$\Delta x = (H^T R^{-1} H)^{-1} H^T R^{-1} \Delta p$$

Error in WLS Solution

$$\mathrm{d}x = (H^T R^{-1} H)^{-1} H^T R^{-1} \mathrm{d}p$$

WLS Solution Covariance

$$\mathrm{cov}(\mathrm{d}x) = (H^T R^{-1} H)^{-1}$$

[1] Kaplan, E., & Hegarty, C. (Eds.). (2005). *Understanding GPS* (2nd ed.)

Thank you

Backup Slides

Antenna Requirements

Pictures of antenna’s in use, and associated band

Applicability to LEO-PNT
LEO PNT transmission in L1

Assessment of Potential System Interference through Radio Frequency Compatibility Analysis on Existing GNSS Frequencies by Emerging LEO Constellations

- **System design must comply with Recommendation ITU-R M.1831**
  - ➢ Effective C/No
  - ➢ C/No degradation

- **Possible to transmit LEO PNT signals in L1 by limiting power levels and modulation method selection to avoid GNSS C/No degradation**

Applicability to LEO-PNT
L-Band considerations

Prior studies….

Gmv LEOPARD Project

- LEO CDMA scenarios lead to **Excessive Multiple Access Interference (MAI).**
- Assuming 60 dB-Hz nominal PoG, **GPS C/A-Like signals lead to a C/No plateaux ~46 dBHz for “OneWeb-like” constellation** (about 14 dB of MAI!)
- S-Band assumed
- -> Higher power CDMA signals from LEO (S-Band) can cause self interference.

Definitions

L, S, C, Ku… bands

Radar-frequency bands according to IEEE standard[17]

Band designation	Frequency range	Explanation of meaning of letters
HF	0.003 to 0.03 GHz	High frequency[18]
VHF	0.03 to 0.3 GHz	Very high frequency[18]
UHF	0.3 to 1 GHz	Ultra-high frequency[18]
L	1 to 2 GHz	Long wave
S	2 to 4 GHz	Short wave
C	4 to 8 GHz	Compromise between S and X
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K_u	12 to 18 GHz	*Kurz*-under
K	18 to 27 GHz	German: *Kurz* (short)
K_a	27 to 40 GHz	*Kurz*-above
V	40 to 75 GHz	
W	75 to 110 GHz	W follows V in the alphabet[20]
mm or G	110 to 300 GHz[note 1]	Millimeter[17]

1. ^ The designation mm is also used to refer to the range from 30 to 300 GHz.[17]

Gennifer to Clean up

521-2002 - IEEE Standard Letter Designations for Radar-Frequency Bands

Prediction of building entry loss ITU-R P.2109-2

Model was developed with empirical data from ITU-R P.2346, and ITU-R P.2040

Traditional vs Modern building construction

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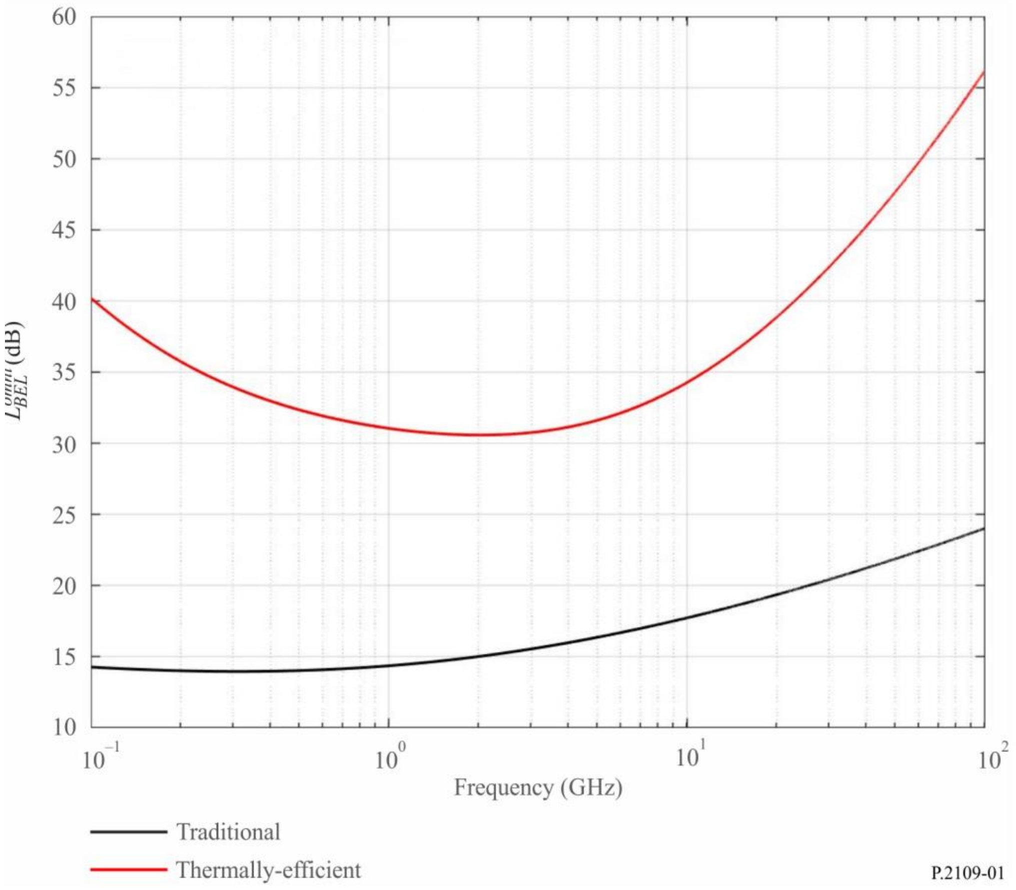
Median building entry loss predicted at horizontal incidence



Recommendation ITU-R P.2109-2 (08/2023)
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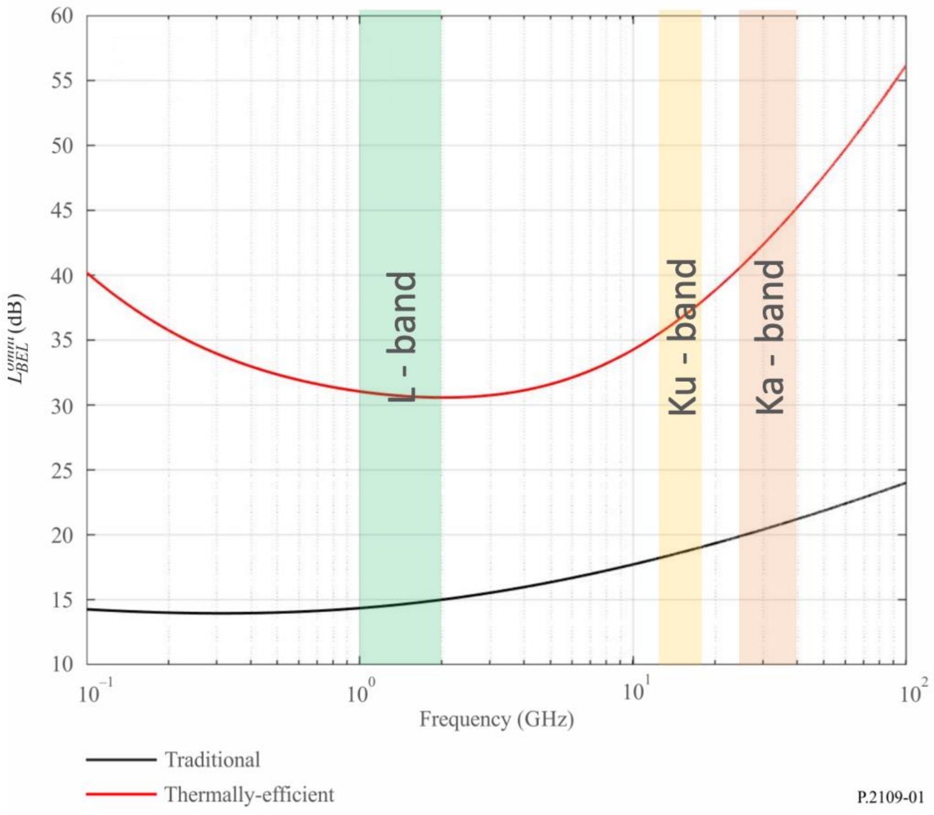

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