IMPULSE TECHNOLOGIES INC.

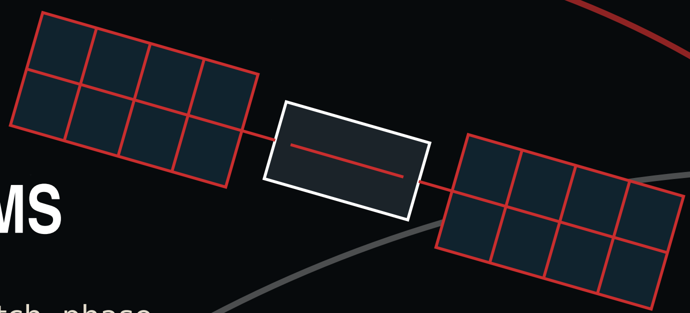
AN INTERNATIONAL COMPANY

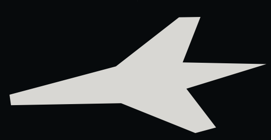
TECHNICAL WHITE PAPER / WP-2026-01 / 2026

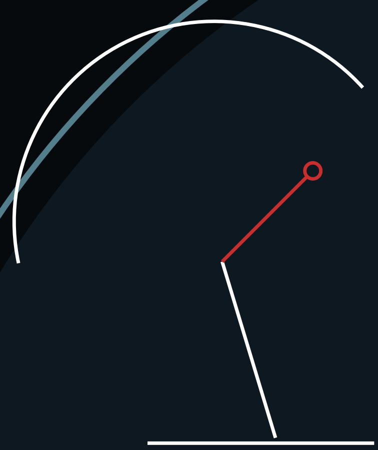
MICROWAVE SIGNAL-PATH ENGINEERING

FOR AEROSPACE SYSTEMS

A practical framework for power, loss, mismatch, phase, interfaces and verification







MICROWAVE / RADAR / SATELLITE COMMUNICATIONS / AEROSPACE

EXECUTIVE SUMMARY

THE SIGNAL PATH IS THE SYSTEM

A disciplined RF architecture treats every interface as part of one measurable power-and-phase chain, from source to aperture and back to the receiver.

This paper provides a general engineering framework for microwave signal paths used in satellite communications, radar, airborne sensors and ground systems. It is written for systems engineers, RF designers, technical buyers and program teams who need to turn component data into defensible system margin.

SCOPE NOTE

The equations and worked cases are educational examples. They do not replace approved drawings, model-specific datasheets, qualification plans or program requirements.

SIX ANALYTICAL FINDINGS

01 **Reference planes are architecture decisions.**

Loss, phase and mismatch cannot be assigned correctly until the electrical boundaries are explicit.

02 **Thermal risk is counted in watts.**

At high input power, even a fraction of a decibel can create a meaningful heat load.

03 **Phase sensitivity rises with frequency.**

Small length or material-property changes create larger electrical phase changes at shorter wavelengths.

04 **Range is a dominant term.**

Free-space communication loss varies with R^-2; a monostatic radar echo varies with R^-4.

05 **Interfaces can dominate good components.**

Adapters, transitions, bends, connectors and torque practices can consume margin not visible in isolated datasheets.

06 **Uncertainty consumes margin too.**

Traceability, verification artifacts and an uncertainty budget are part of the result, not laboratory paperwork.

ARCHITECTURE

DEFINE THE ELECTRICAL BOUNDARY

A signal-path budget is only as clear as its reference planes, operating states and environmental assumptions.

END-TO-END FUNCTIONAL CHAIN

SOURCE	CONTROL	INTERFACE	APERTURE	CHANNEL	RECEIVER
power / spectrum	level / phase	coax / waveguide	gain / pattern	range / medium	noise / linearity

FOUR QUESTIONS BEFORE THE FIRST CALCULATION

01 What is inside?

List every cable, connector, adapter, switch state, limiter, coupler and transition between declared planes.

02 What is the operating state?

Specify frequency, bandwidth, duty factor, modulation, peak/average power and simultaneous modes.

03 What environment applies?

Define temperature, pressure or vacuum, vibration, radiation, EMC and mounting boundary conditions.

04 What is verified?

Name the calibrated quantity, method, uncertainty, pass/fail rule and model-specific acceptance record.

NASA's 2026 small-spacecraft communications guidance describes link-budget trades that vary antenna size, RF output power and data rate, with each configuration returning a margin. The same discipline should extend inward through the hardware chain so that the link margin is traceable to physical interfaces.

Source: NASA, 2026 State-of-the-Art Small Spacecraft Technology, Communications chapter.

FUNDAMENTALS

WORK IN DB - CHECK IN WATTS

Decibels make cascaded gains and losses easy to audit; linear power makes energy balance and heating visible.

`G[dB] = 10 log10(P2/P1)`

Power ratio. Use 20 log10 only for a voltage or field ratio under cons

`P[dBm] = 10 log10(P[mW])`

Absolute power referenced to 1 mW. Therefore 0 dBm = 1 mW and 30 dBm =

A BUDGET IS A SIGNED LEDGER

+	**Transmitter output**	available conducted power
-	**Cable / switch / adapter**	measured or allocated insertion loss
+	**Transmit antenna**	gain in the stated direction and polarization
-	**Propagation and atmosphere**	free space plus applicable medium losses
+	**Receive antenna**	receive gain under the same geometric assumptions
-	**Receiver path**	feed, filter and transition loss before the noise reference plane

ENGINEERING CHECK

After the dB budget closes, convert critical nodes back to watts. Confirm that dissipated power, peak voltage/current, connector ratings, device compression, duty cycle and thermal paths remain inside the approved operating envelope. A positive link margin does not prove that the hardware is thermally or electrically safe.

MISMATCH

RETURN LOSS IS POWER FLOW

Reflection coefficient, return loss and VSWR are different views of the same interface behavior.

`Gamma = (ZL-Z0)/(ZL+Z0)`

Complex reflection coefficient at the declared

`RL = -20 log10|Gamma|`

Return loss in dB; larger positive values indic

`Pref/Pin = |Gamma|^2`

Reflected fraction. Accepted power is Pin(1-|Gamm

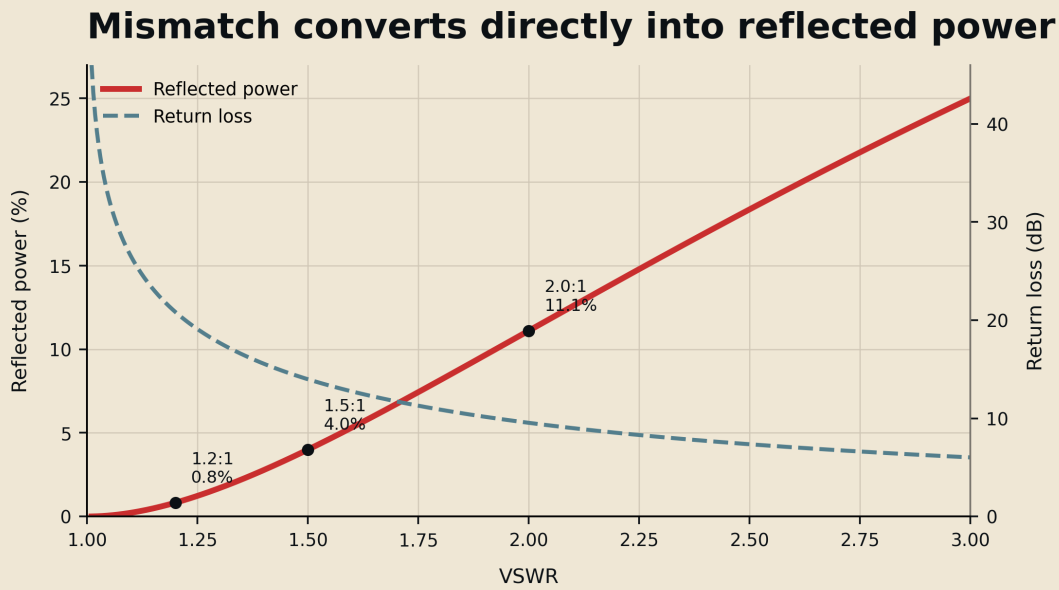


Figure 1. Analytical conversion among VSWR, return loss and reflected-power fraction.

WHAT A SINGLE S11 TRACE DOES NOT SETTLE

- **Reference-plane location:** cable and adapter loss can make a remote interface appear better matched than it is.
- **Operating state:** power, temperature, switching state and mechanical torque can move the result.
- **Interaction:** multiple reflections between discontinuities can create frequency-selective ripple and phase error.
- **System consequence:** mismatch can reduce accepted power, increase standing-wave voltage and change amplifier loading.

LOSS AND HEAT

FOLLOW THE MISSING WATTS

Insertion loss is a system penalty and, where energy is absorbed, a thermal design input.

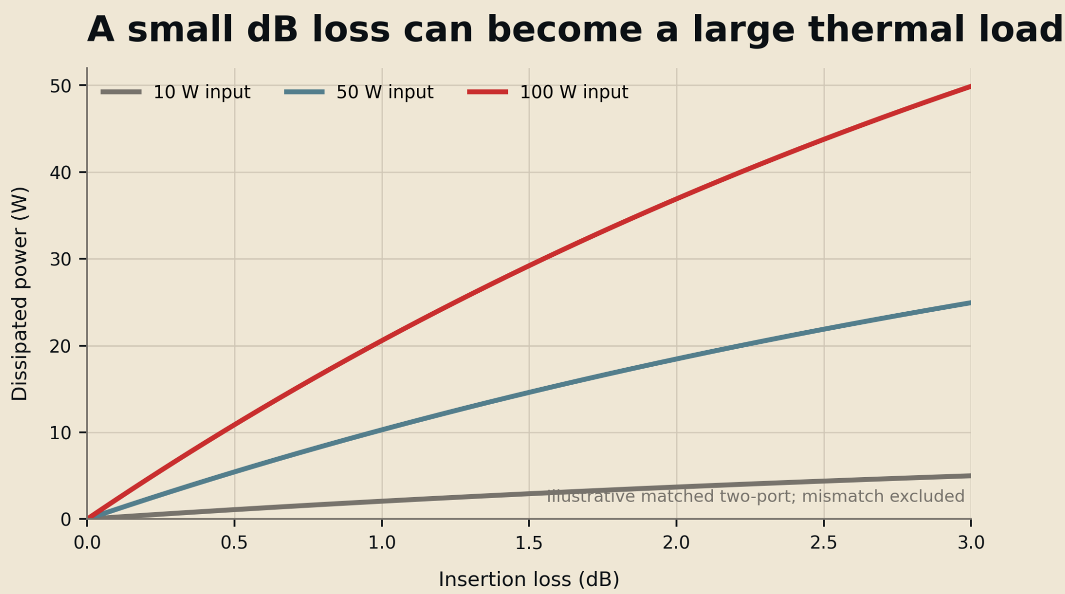


Figure 2. Dissipation implied by insertion loss for an illustrative matched passive path. Reflected power and other ports are excluded.

ENERGY-BALANCE VIEW

Pabs = Pin - Pout - Pref - Pother ports

For a passive multiport, account for every measured output and reflected term before assigning the remainder to heat.

01 Average vs peak

Thermal rise follows time-averaged dissipation and the transient thermal network; voltage breakdown and compression may follow peak conditions.

02 Mounting matters

The same component can run at a different temperature when interface flatness, fastener preload, heat spreading or airflow changes.

03 Temperature feeds back

Conductor loss, dielectric loss and dimensional change can shift insertion loss and phase while the hardware warms.

PHASE

ELECTRICAL LENGTH IS AN ENVIRONMENTAL VARIABLE

Physical length, propagation constant and frequency jointly determine phase; each can move under aerospace conditions.

phi = beta l = 2 pi l/lambda_g

Electrical phase for a uniform propagation path.

Delta phi approx beta Delta l + l Delta beta

First-order sensitivity to dimensional and propagation-constant change.

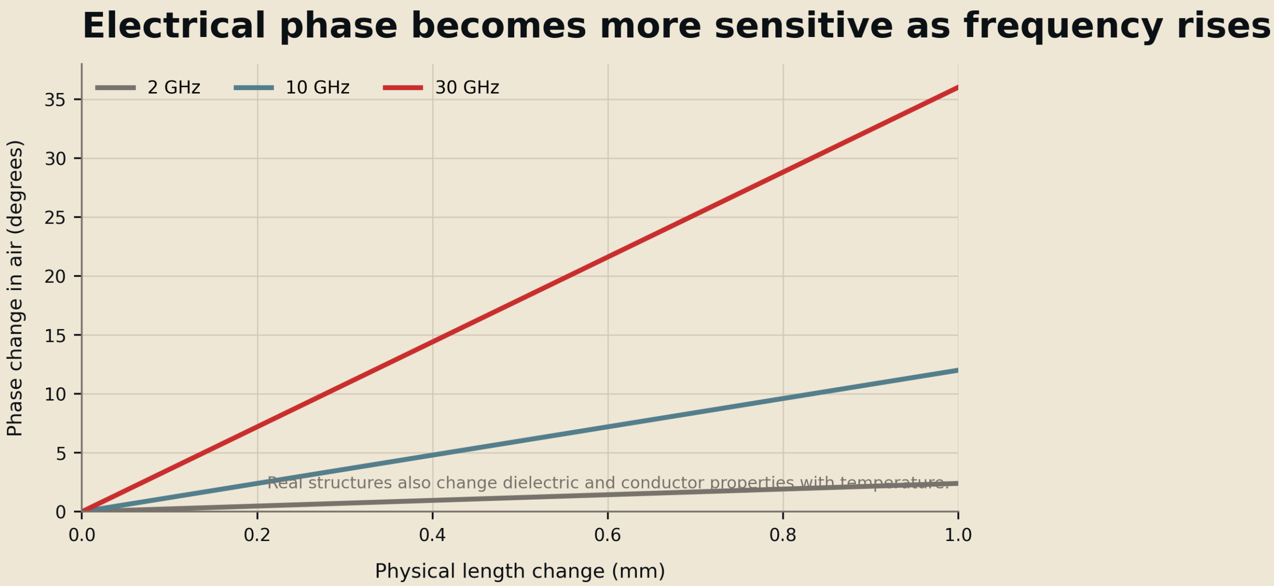


Figure 3. Phase change from physical length change in air. Guided structures require their own propagation model.

PHASE-STABILITY REVIEW

01 Material

thermal expansion; dielectric temperature coefficient; plating and conductivity

02 Geometry

cable routing; bend radius; waveguide flange flatness; mechanical preload

03 Measurement

calibration drift; cable flexure; connector repeatability; reference-plane transfer

04 System

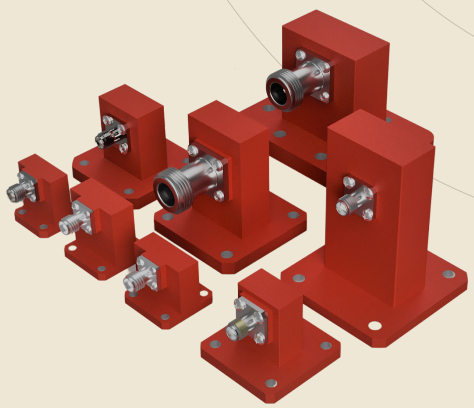
beam-pointing error; coherent combining loss; calibration residual; timing bias

INTERFACES

COAX AND WAVEGUIDE SHARE ONE BUDGET

Transitions do more than change geometry: they move reference planes, introduce modes and add assembly sensitivity.

A transition should be reviewed as a network, not a mechanical convenience. Define its port modes, frequency range, orientation, flange or connector condition, insertion loss, return loss, phase and power boundary. If an adapter is used during test but not in flight, de-embed it with a stated method and uncertainty.



REFERENCE-PLANE RULE

Place each budget boundary where a requirement can be measured, assigned to an owner and reproduced after integration

INTERFACE CHECKLIST

01 Connector or flange

series, gender, torque, flatness, finish and mating-life assumptions

02 Mode control

dominant mode, cutoff margin, higher-order-mode risk and bend orientation

03 Assembly

alignment, gasket or choke details, fastener sequence and cleanliness

04 Test removal

fixture characterization, port extension or de-embedding method and residual uncertainty

05 Configuration

model, frequency band, switch state, temperature and mechanical mounting

06 Evidence

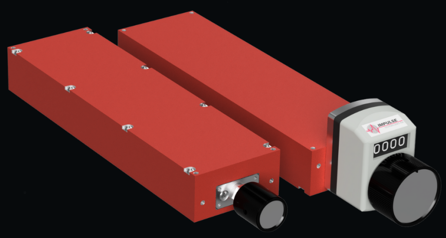
raw calibrated data, plots, serial number, calibration state and acceptance disposition

HIGH POWER

DESIGN FOR THE FAILURE MECHANISM

Average power, peak field, pressure, geometry, contamination and thermal impedance can govern different limits.

High-power microwave hardware should not be reduced to a single wattage. The applicable limit depends on waveform, duty factor, pulse width, frequency, load mismatch, ambient pressure, temperature, mounting and the exact model geometry.



MODEL-SPECIFIC EVIDENCE

Use the approved drawing and test record for the selected model. Do not transfer a power claim between frequency bands, connector options, housings or duty cycles without engineering justification.

FAILURE-MODE MAP

01 Conductor heating

I^2R loss, current concentration and limited heat rejection

02 Dielectric heating

loss tangent, electric-field distribution and thermal runaway

03 Breakdown / corona

pressure, gap, field enhancement, contamination and waveform

04 Multipaction

vacuum electron resonance dependent on geometry, field and surface

05 Passive intermodulation

nonlinear contacts, dissimilar materials, contamination and current density

06 Compression / nonlinearity

control elements or ferrites driven outside the characterized small-signal state

NASA's spacecraft high-voltage guidance emphasizes pressure- and geometry-dependent corona or Paschen considerations; program-specific analysis and testing remain essential.

PROPAGATION

THE APERTURE CONNECTS HARDWARE TO RANGE

Antenna gain, pointing, polarization and free-space loss connect the conducted RF chain to the mission geometry.

Lfs[dB] = 92.45 + 20log fGHz + 20log dkm

Free-space basic transmission loss using GHz and km.

EIRP[dBW] = Pt + Gt - Lt

Conducted transmit power plus antenna gain minus loss before the aperture.

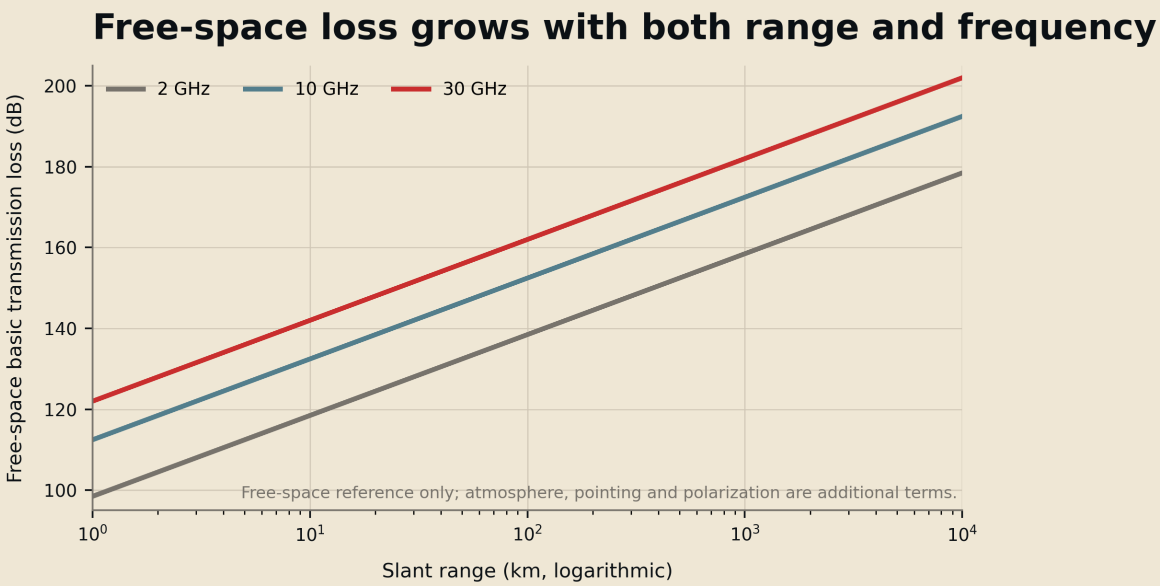


Figure 4. Free-space reference computed from ITU-R P.525-5. It excludes atmosphere, rain, scintillation, polarization and pointing loss.

DO NOT HIDE THESE TERMS INSIDE 'MARGIN'

- antenna pattern at the actual look angle
- polarization alignment and axial ratio
- pointing knowledge, control error and structural deflection
- atmospheric gas, rain, cloud and scintillation where applicable
- radome or window loss across angle, temperature and moisture
- implementation, aging and measurement uncertainty allocations

Sources: ITU-R P.525-5 (2024); NASA 2026 Small Spacecraft Communications chapter.

WORKED EXAMPLE

A ONE-WAY SATELLITE LINK

An illustrative X-band ledger demonstrates how internal hardware terms and propagation combine. Values are not a program prediction.

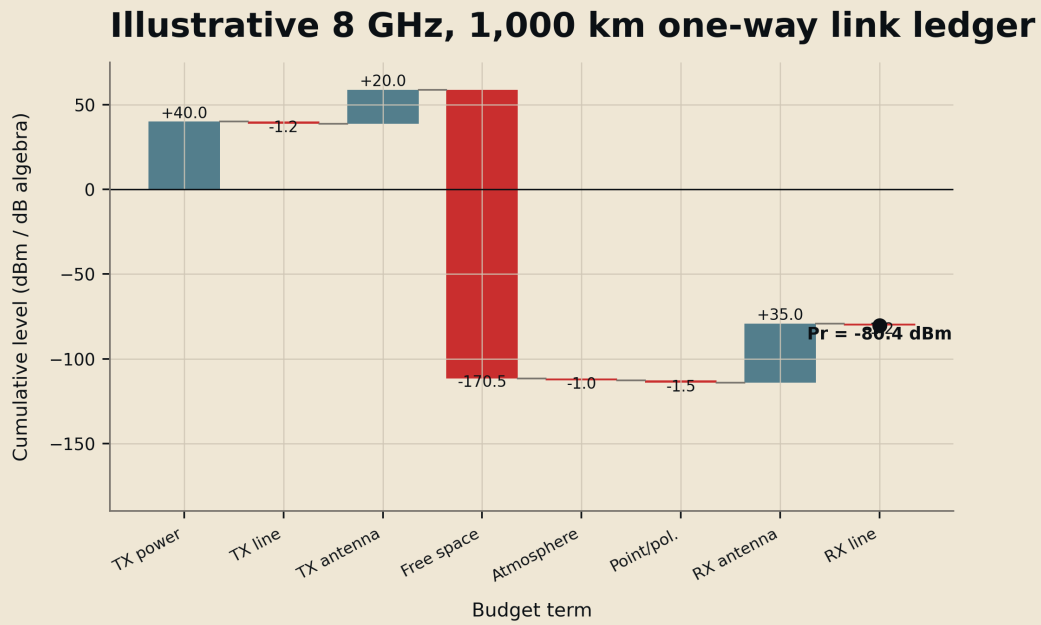


Figure 5. Illustrative 8 GHz, 1,000 km link. Positive terms add power or antenna gain; negative terms consume it.

ASSUMPTIONS AND RESULT

Transmit power	40.0 dBm (10 W)
TX internal loss	1.2 dB
TX antenna gain	20.0 dBi
Atmosphere	1.0 dB
Pointing / polarization	1.5 dB
RX antenna gain	35.0 dBi

Pr = -80.4 dBm

Received level at the declared receiver reference plane.

NEXT STEP

Compare against the required Eb/N0 or C/N0 using bandwidth, data rate, noise temperature, modulation, coding and implementation loss.

NASA notes that link-budget trades commonly vary antenna size, RF output power and data rate, with rain and atmospheric attenuation included where relevant.

RADAR

THE RETURN PATH DOUBLES THE CONSEQUENCE

In a simplified monostatic radar equation, received target power falls with the fourth power of range.

```
Pr = Pt G^2 lambda^2 sigma / ((4 pi)^3 R^4 L)
```

Simplified monostatic radar equation. Real systems may require propagation, pattern, processing, fluctuation and clutter terms.

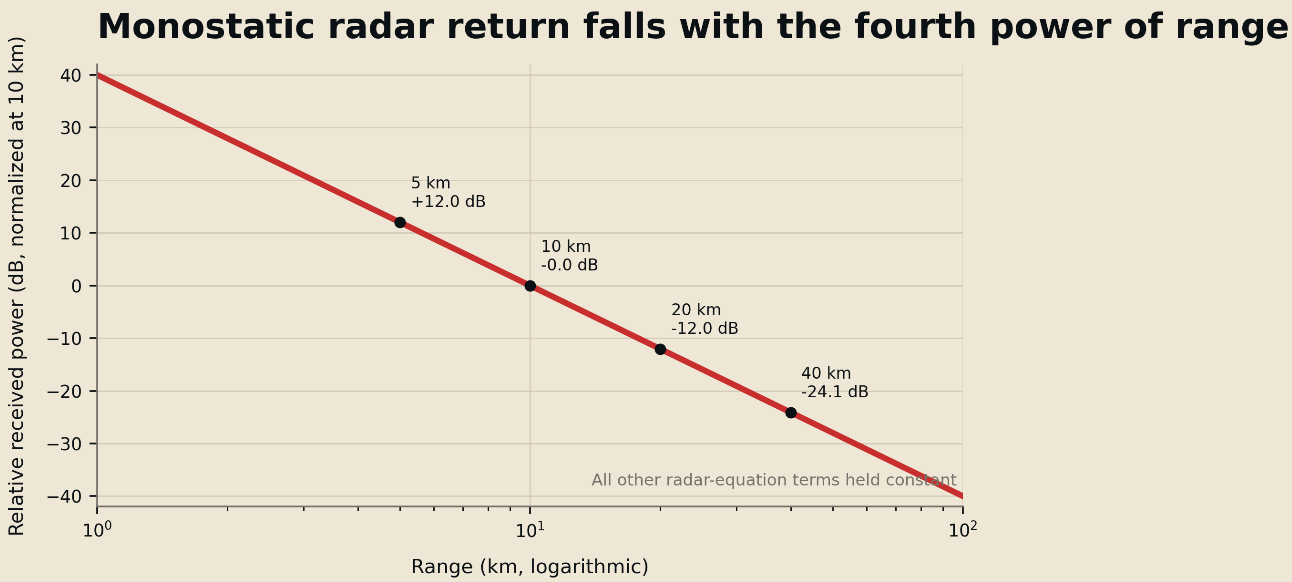


Figure 6. Relative radar return with all non-range terms fixed. Doubling range reduces return by approximately 12.0 dB.

SYSTEM CONSEQUENCES

01 Two-way hardware

Transmit and receive insertion losses may appear on different reference planes or share a duplexing path.

02 Isolation

Leakage, limiter recovery and duplexer isolation can determine whether weak echoes remain observable.

03 Coherence

Phase noise, timing, channel-to-channel phase and calibration stability influence coherent processing.

04 Noise and clutter

Thermal noise is kTB before receiver noise figure; clutter and interference require separate models.

Reference: NASA/JPL DESCANSO, Synthetic Aperture Radar Imaging Basics, Section 1.3.

AEROSPACE ENVIRONMENT

QUALIFY THE CONFIGURATION YOU WILL FLY

Environmental verification must preserve the electrical configuration, mounting conditions and measurement references that define performance.

STRESS - MECHANISM - OBSERVABLE

STRESS	PHYSICAL MECHANISM	RF OBSERVABLE / EVIDENCE
Temperature / vacuum	expansion, conductivity, dielectric change, limited convection	loss, phase, match, temperature, breakdown
Vibration / shock	fastener relaxation, cable motion, contact damage, misalignment	continuity, S-parameters, torque witness, inspection
Pressure transition	corona susceptibility in critical pressure regimes	partial discharge or approved high-voltage test evidence
EMI / EMC	conducted and radiated coupling through cables, structure and apertures	emissions, susceptibility and grounding/bonding verification
Radiation / charging	material, dielectric and electronic-state change	mission-specific analysis, shielding and test evidence

VERIFICATION PRINCIPLE

Tailor test levels and methods to the actual mission and governing program requirements. GSFC-STD-7000B provides an environmental-verification framework for payloads, subsystems and components; MIL-STD-461 establishes EMI emission and susceptibility interface and verification requirements for DoD equipment. Verify the current applicable revision before use.

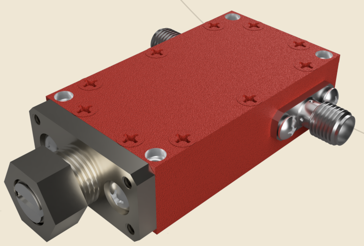
Sources: GSFC-STD-7000B; MIL-STD-461G document record; NASA-HDBK-4001.

MEASUREMENT

TRACEABILITY STARTS AT THE REFERENCE PLANE

A calibrated instrument is necessary, but the result also depends on standards, fixtures, drift, repeatability and uncertainty propagation.

S-parameters describe a linear network at its calibrated ports. For aerospace hardware, the useful record is more than a screenshot: it identifies the DUT, configuration, calibration method, reference planes, frequency grid, power, temperature, cables or fixtures, uncertainty and disposition.



```
uc = sqrt(sum((ci ui)^2))
```

Combined standard uncertainty for uncorrelated input quantities, using sensitivity coefficients ci.

MINIMUM DATA PACKAGE

- **01** serial number and model configuration
- **02** ports, modes and reference-plane diagram
- **03** calibration type, standards and due status
- **04** raw complex data plus rendered plots
- **05** temperature, power, torque and test state
- **06** uncertainty, guard band and pass/fail rule
- **07** fixture removal or de-embedding method
- **08** operator, date, equipment and software versions

WHY VERIFICATION ARTIFACTS MATTER

NIST describes VNA verification by measuring artifacts characterized with traceable calibrations and comparing the result with traceable values. This separates a calibration that completed from a measurement system that continues to perform as expected.

Sources: NIST Technical Note 1297; NIST TN 2109; NIST, Electronic Vector-Network-Analyzer Verification.

ENGINEERING WORKFLOW

FROM REQUIREMENT TO ACCEPTANCE

The strongest program evidence is a closed chain from mission need to reference plane, analysis, hardware configuration and verified result.

01

MISSION

range, waveform, sensitivity, environment

02

BOUNDARIES

ports, modes, reference planes, ownership

03

BUDGET

power, loss, phase, noise and uncertainty

04

DESIGN

components, transitions, thermal and mechanical interfaces

05

VERIFY

calibrated method, configuration, environment and guard band

06

CONTROL

serial data, revision, acceptance and change impact

TECHNICAL PROCUREMENT CHECKLIST

- Does the requested frequency range match the exact interface and mode?
- Are insertion loss, return loss, phase and power conditions stated at compatible planes?
- Is the load mismatch and duty factor defined for high-power operation?
- Are temperature and mechanical mounting conditions part of the requirement?
- Can model-specific data and acceptance evidence be supplied for the chosen configuration?
- Does the pass/fail rule account for measurement uncertainty and guard band?
- Are adapters, cables and fixtures included in - or removed from - the requirement explicitly?
- Will post-environment testing use the same ports, state and analysis method?

DECISION GATE

Do not release the interface until each critical budget term has an owner, value, condition, verification method and controlled evidence path.

CONCLUSIONS AND REFERENCES

ENGINEER THE CHAIN - NOT THE CATALOG

Microwave performance becomes credible when power, phase, interfaces, environment and uncertainty are treated as one controlled system.

The central conclusion is practical: component specifications do not automatically become system performance. Reference planes, operating states, transition hardware, thermal paths, environmental changes and measurement uncertainty determine how the signal path behaves after integration.

PRIMARY REFERENCES

1. ITU-R P.525-5, Calculation of Free-Space Attenuation, November 2024. itu.int/rec/R-REC-P.525-5-202411-I/en
2. NASA, 2026 State-of-the-Art Small Spacecraft Technology - Communications. nasa.gov/smallsat-institute/sst-soa/soa-communications/
3. NASA, State-of-the-Art Small Spacecraft Technology, 2026 edition. nasa.gov/smallsat-institute/sst-soa/
4. NASA/JPL DESCANSO, Synthetic Aperture Radar Imaging Basics, Section 1.3, Radar Equation. descanso.jpl.nasa.gov/SciTechBook/series2/
5. NIST Technical Note 1297, Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results, 1994 edition. nist.gov/pml/nist-technical-note-1297
6. Jargon et al., NIST TN 2109, Physical Models and Dimensional Traceability of WR15 Rectangular-Waveguide Standards, 2020. doi.org/10.6028/NIST.TN.2109
7. Williams et al., Electronic Vector-Network-Analyzer Verification, NIST. nist.gov/document/05235824pdf
8. NASA-HDBK-4001, Electrical Grounding Architecture for Unmanned Spacecraft.
9. GSFC-STD-7000B, General Environmental Verification Standard for GSFC Flight Programs and Projects, 2021.
10. MIL-STD-461G, Requirements for the Control of Electromagnetic Interference Characteristics of Subsystems and Equipment, official ASSIST record.

ABOUT IMPULSE TECHNOLOGIES

Impulse Technologies, Inc. supports RF and microwave programs with in-house phase shifters, variable attenuators, amplifiers, power dividers and combiners, directional couplers, hybrids and custom assemblies. Founded in 1991 and based in Bay Shore, New York.

IMPULSE TECHNOLOGIES INC.
AN INTERNATIONAL COMPANY

impulse-tech.com / sales@impulse-tech.com / +1 (631) 968-4116

1989 Union Blvd., Bay Shore, NY 11706 USA