RF Propagation in Enclosed Metallic Structures

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Questions to be addressed

- What factors affect RF propagation inside small metallic structures with complex shapes (such as an airplane wing)?
- How significant is signal attenuation and distortion?
- What are the tradeoffs between RF power, data rate, and carrier frequency?

Measurement procedure

•Two identical antennas (one transmit and one receive), placed at various locations such as on top of the airplane wing or embedded within an airplane wing.

-Experiments performed using a salvaged wing from and S3 Viking aircraft.
-Commercial antennas operating at 900 MHz or 2.4 GHz.

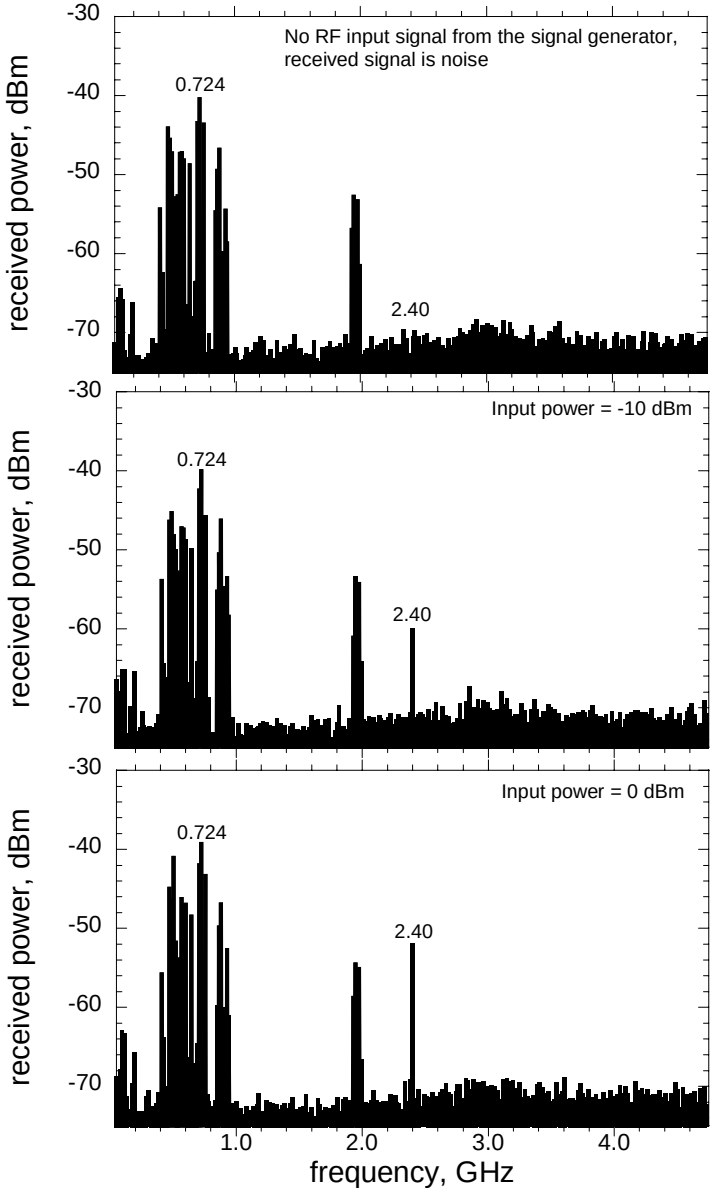
•Modulated RF signal transmitted using an Agilent E8267D PSG Signal Generator, and detected using an Agilent E4446A PSA Spectrum Analyzer.

-Binary phase shift key (BPSK) modulation.

-Symbol rates are either 1 kilo sample per second (ksps), 1 mega sample per second (Msps), or 10 mega samples per second.

-Root Nyquist filters on both the transmit and receive portions of the link.

Background RF noise in NASA-GRC Hangar

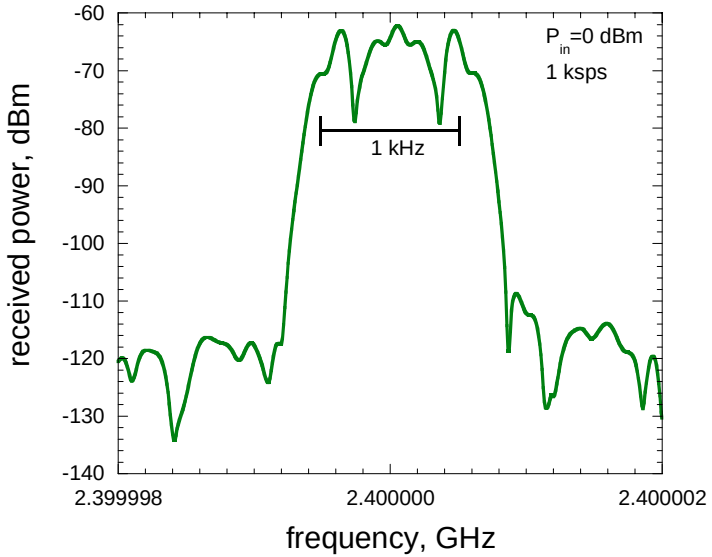


- RF background noise in the NASA-GRC Hangar is substantial.
- Noise is especially high in the 0.4 - 1 GHz ranges, and close to 2 GHz.

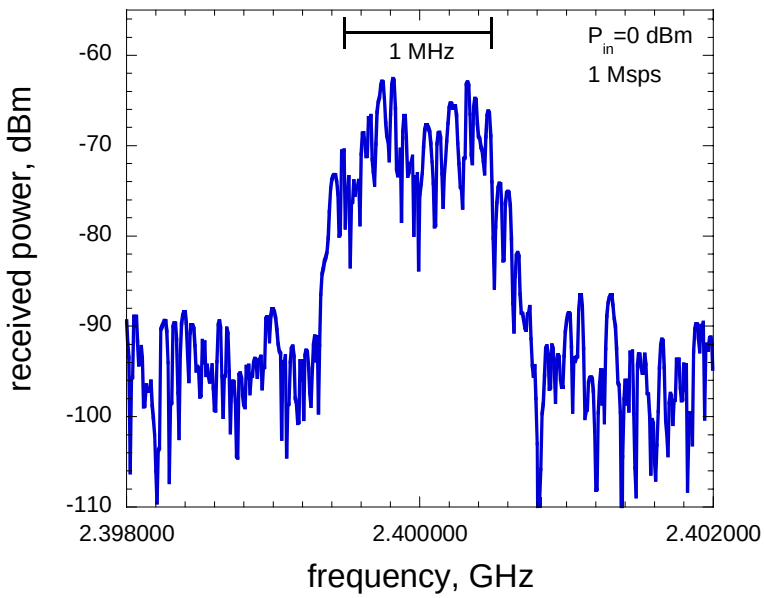
Locations of 2.4 GHz transmit (left) and receive (right) antennas. The 2.4 GHz RF input power was either a) completely off; b) -10 dBm; or c) 0 dBm.

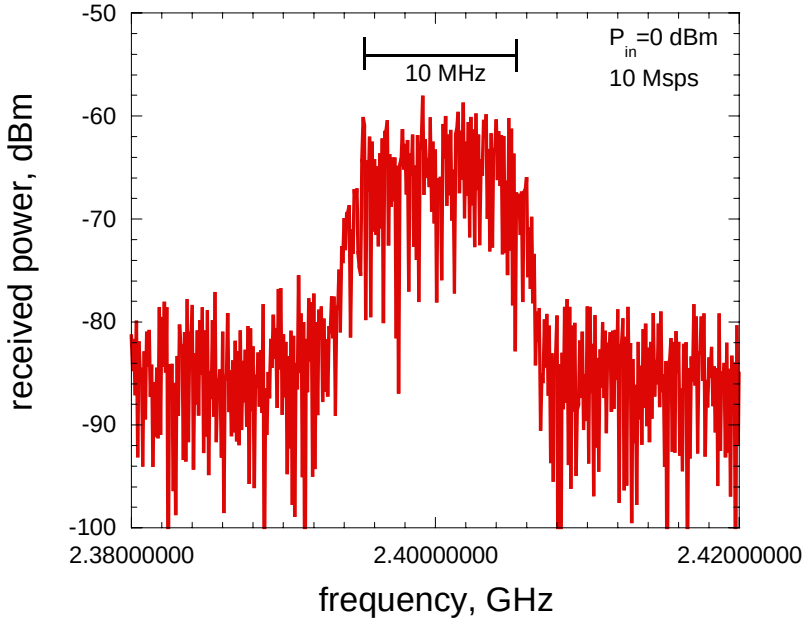
Spectrum analysis of modulated signal

2.4 GHz transmit and receive antennas mounted on top of wing
Distance between monopole antennas = 208 cm



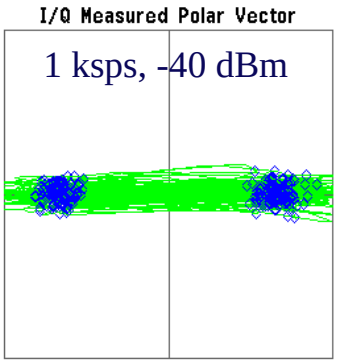
- Increasing data rate reduces the signal-to-noise
- Objective is to establish the minimum power levels at which the signal-to-noise is acceptable.
  - -Transmit power
  - -Interference due to multiple reflections.
  - -Attenuation due to barriers (e.g. airplane ribs).
  - -RF propagation inside small metallic enclosures.

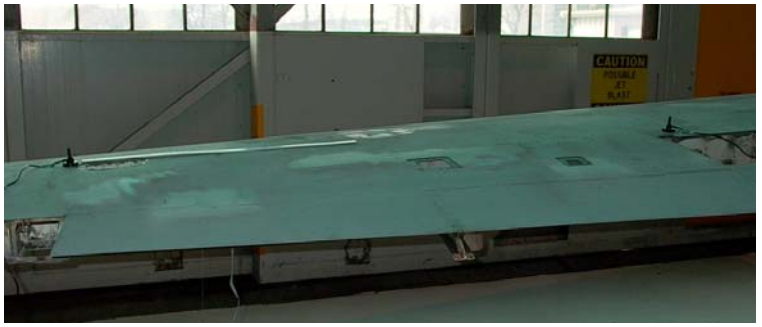


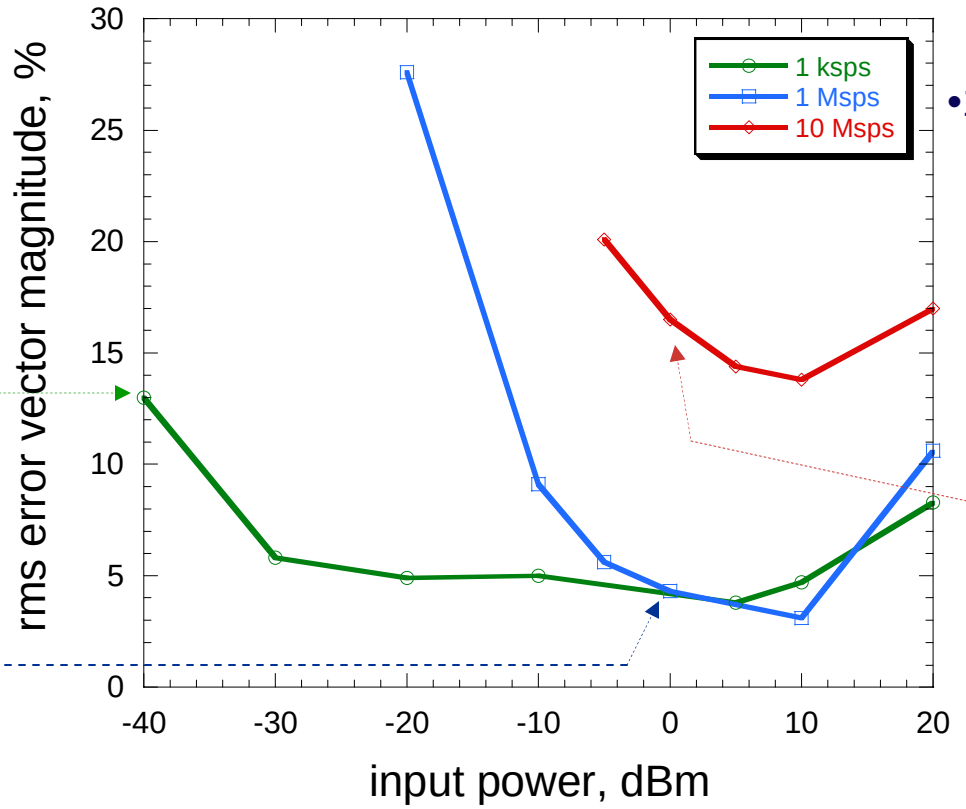


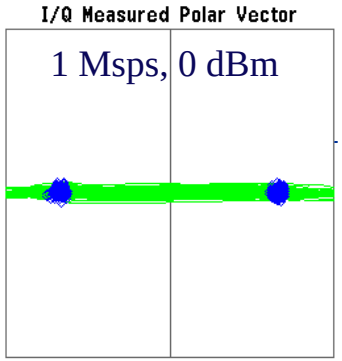
2.4 GHz transmit and receive antennas mounted on top of wing

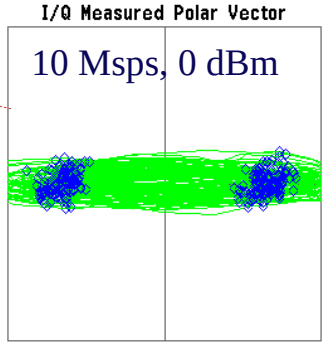
Distance between monopole antennas = 208 cm











- 1 ksps link supported by -40 dBm transmit power
- 1 Msps link supported by -10 dBm transmit power
- 10 Msps link is marginally acceptable at 0 dBm transmit power

2.4 GHz transmit and receive antennas embedded inside wing

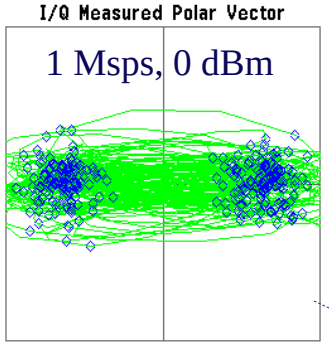
Distance between monopole antennas = 208 cm

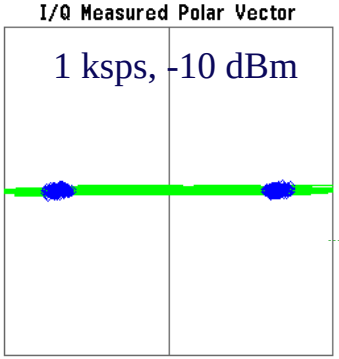
No direct line-of-sight between antennas

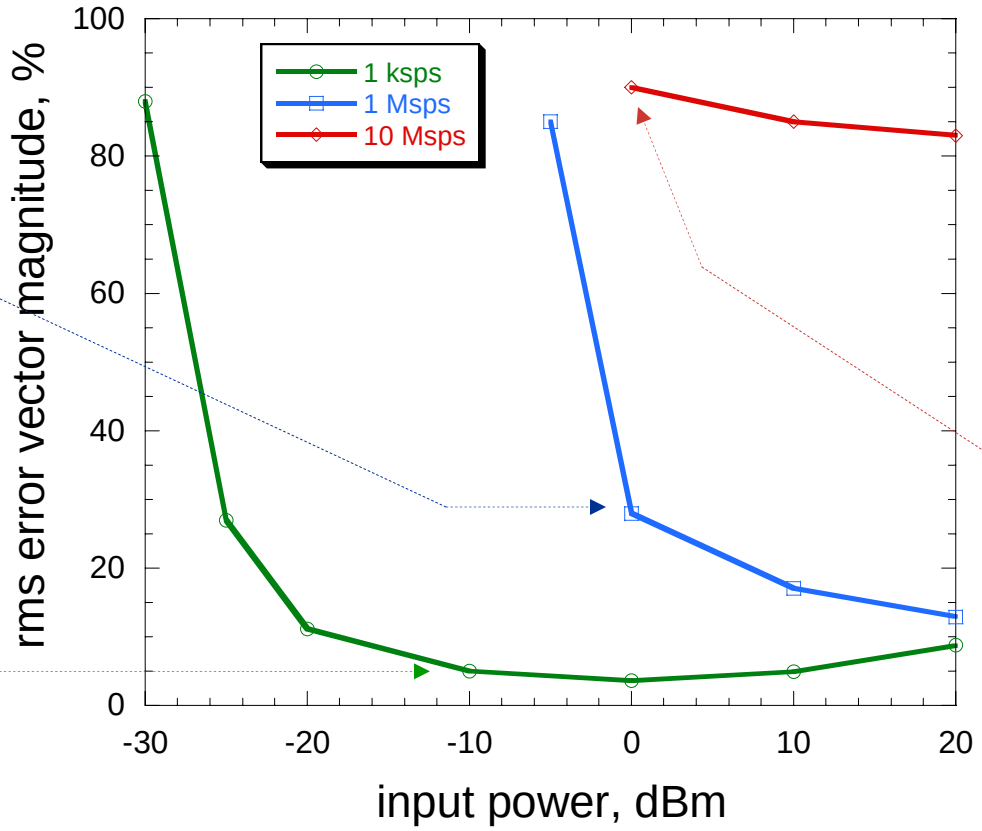
transmit

receive

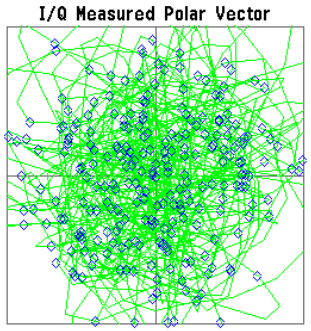
- 1 ksps link supported by -20 dBm transmit power
- 1 Msps link marginally supported by +10 dBm transmit power
- 10 Msps link is unacceptable at all transmit powers







10 Msps, 0 dBm



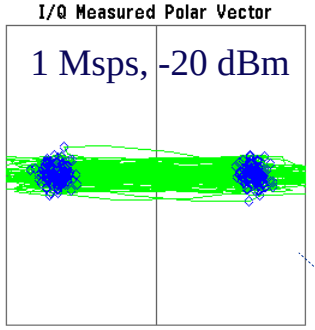
2.4 GHz transmit and receive antennas embedded inside wing

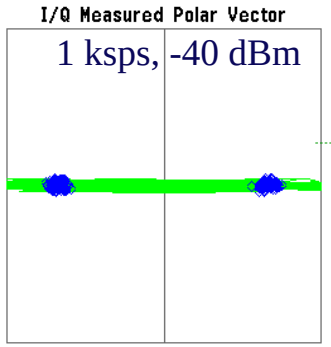
Distance between monopole antennas = 80 cm

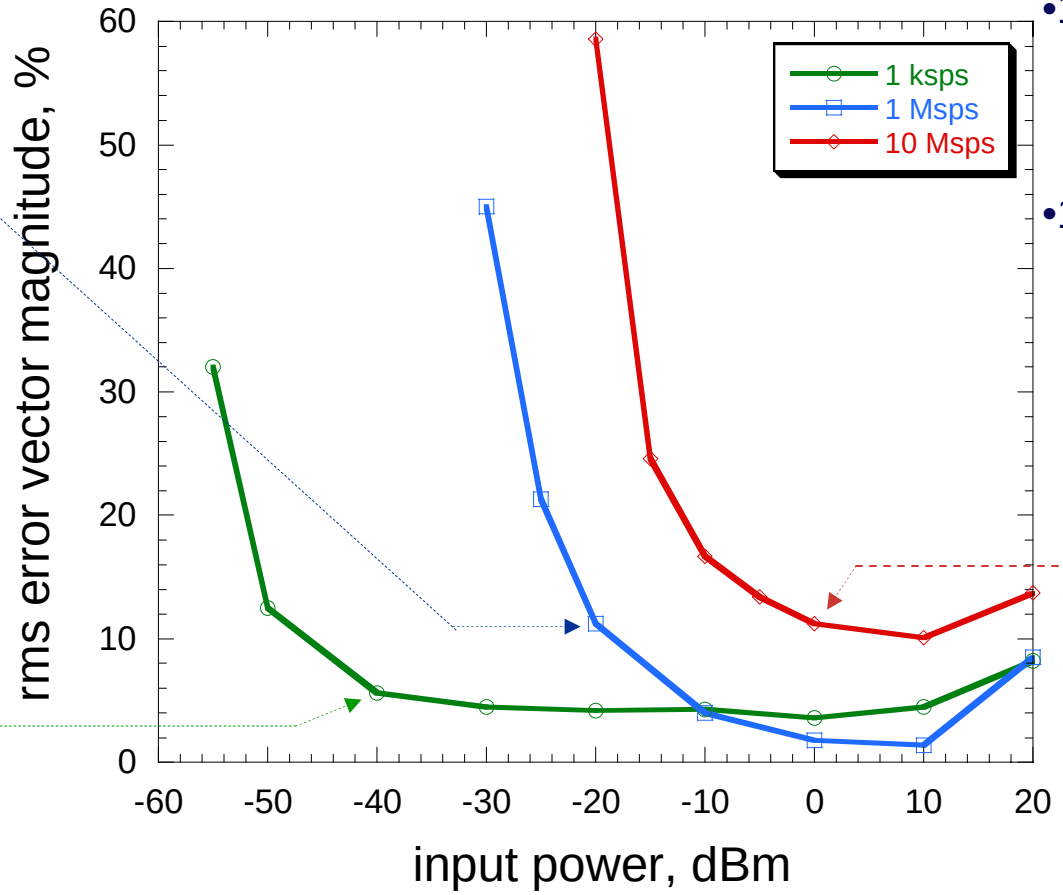
Direct line-of-sight between antennas

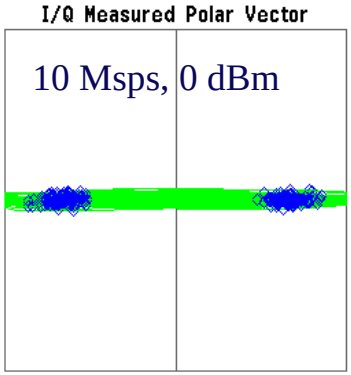
- 1 ksps link supported by -40 dBm transmit power
- 1 Msps link supported by -10 dBm transmit power
- 10 Msps link supported by 0 dBm transmit power

10 dB higher data rate achievable by increasing RF input power by 10 dB



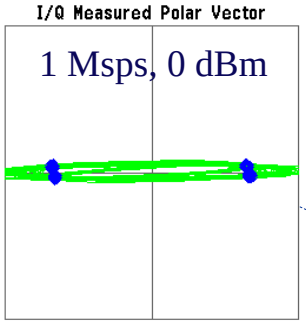


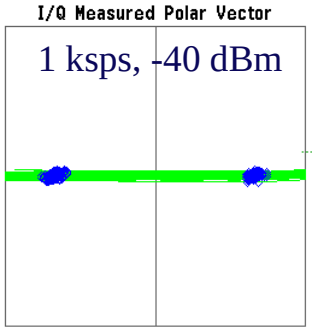


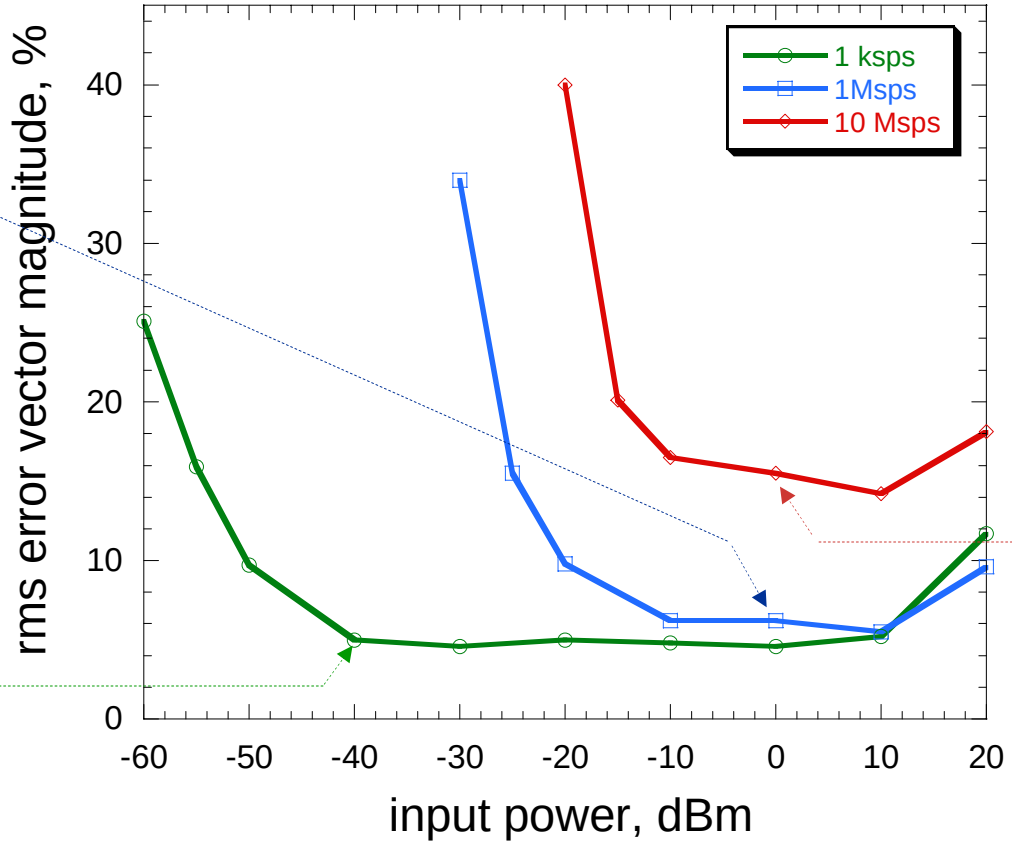


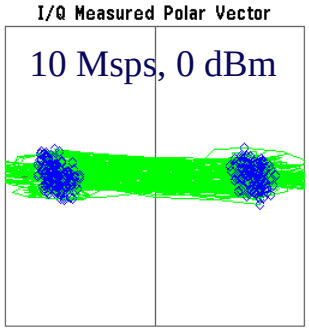
900 MHz transmit and receive antennas mounted on top of wing

Distance between monopole antennas = 208 cm







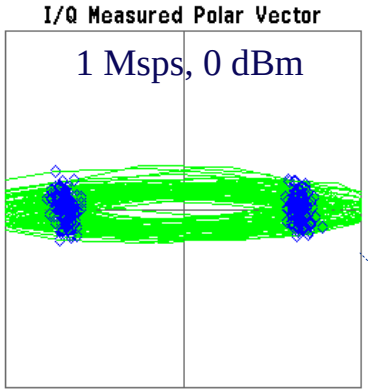


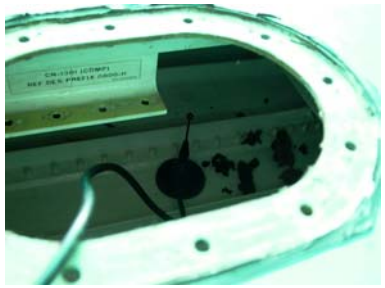
- 1 ksps link supported by -50 dBm transmit power
- 1 Msps link supported by -20 dBm transmit power
- 10 Msps link is marginally acceptable at -10 dBm transmit power

900 MHz transmit and receive antennas embedded inside wing

Distance between monopole antennas = 208 cm

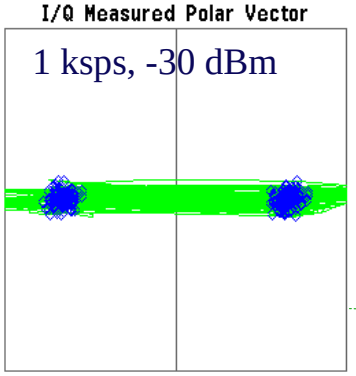
No direct line-of-sight between antennas

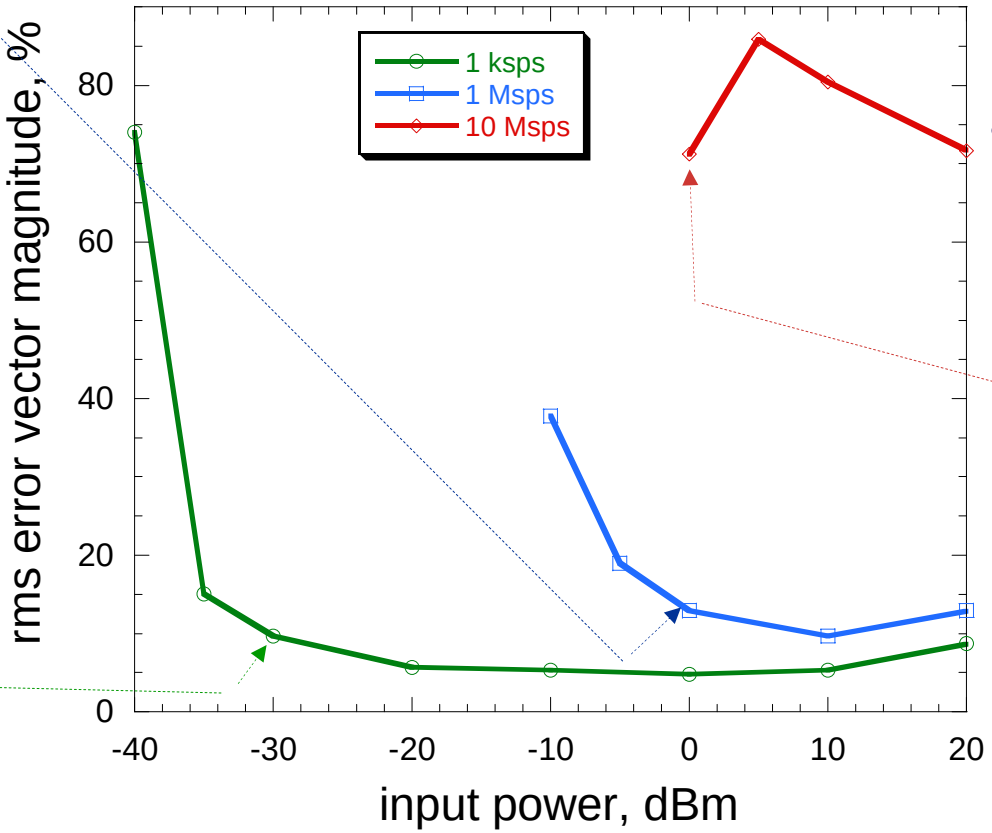


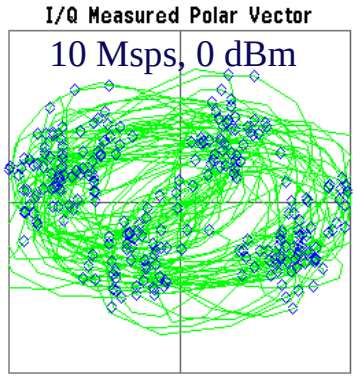


transmit

receive

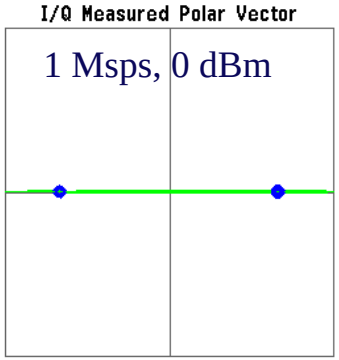


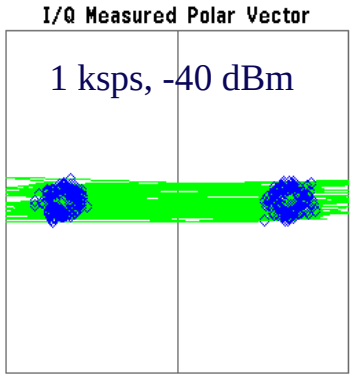


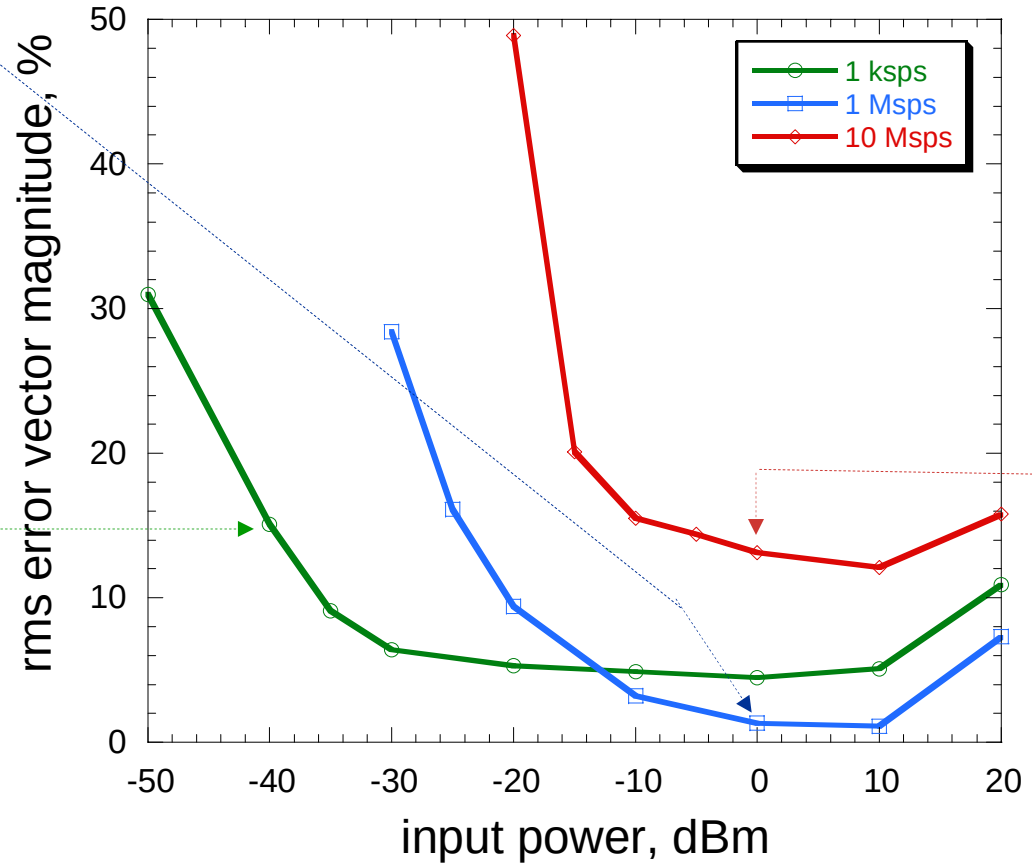


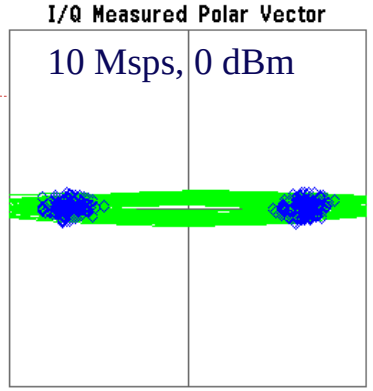
- 1 ksps link supported by -30 dBm transmit power
- 1 Msps link marginally supported by 0 dBm transmit power
- 10 Msps link is unacceptable at all transmit powers

900 MHz transmit and receive antennas embedded inside wing
Distance between monopole antennas = 80 cm
Direct line-of-sight between antennas





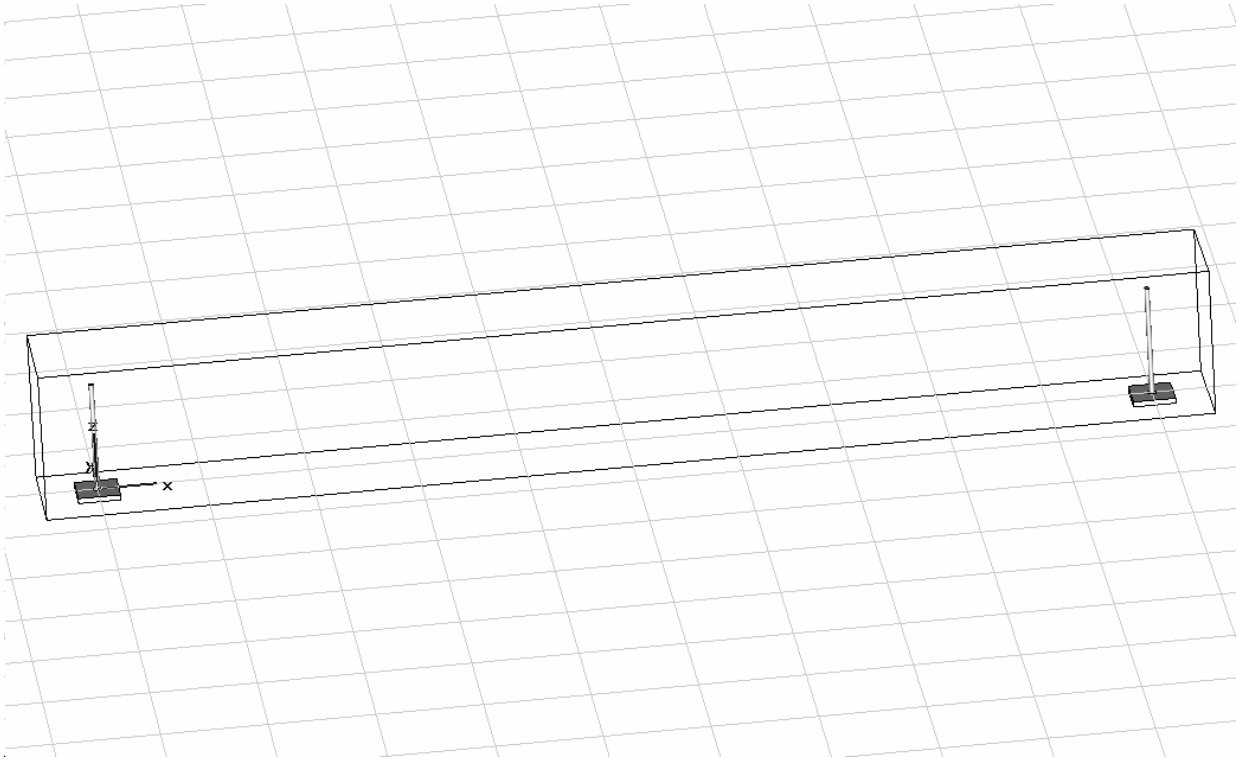




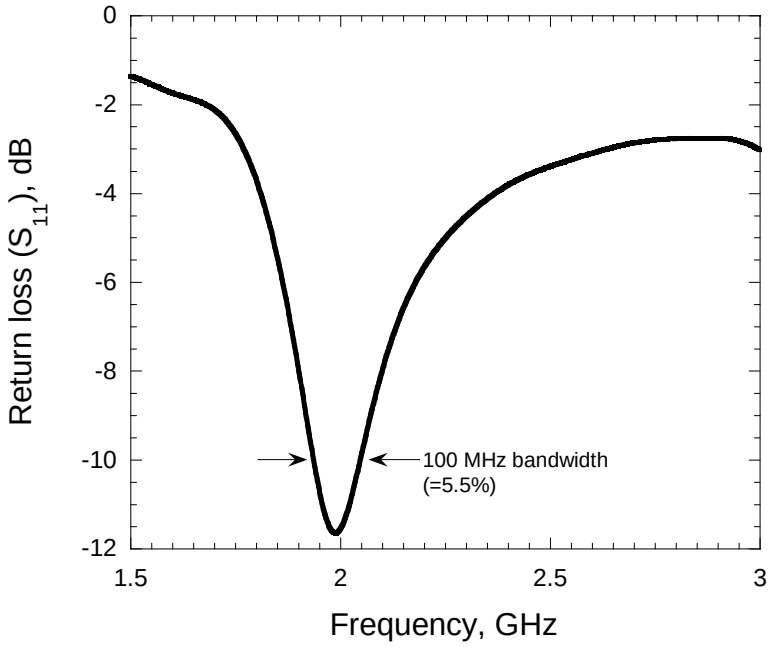
- 1 ksps link supported by -40 dBm transmit power
- 1 Msps link supported by -25 dBm transmit power
- 10 Msps link supported by -10 dBm transmit power

Isolated Monopole Antenna

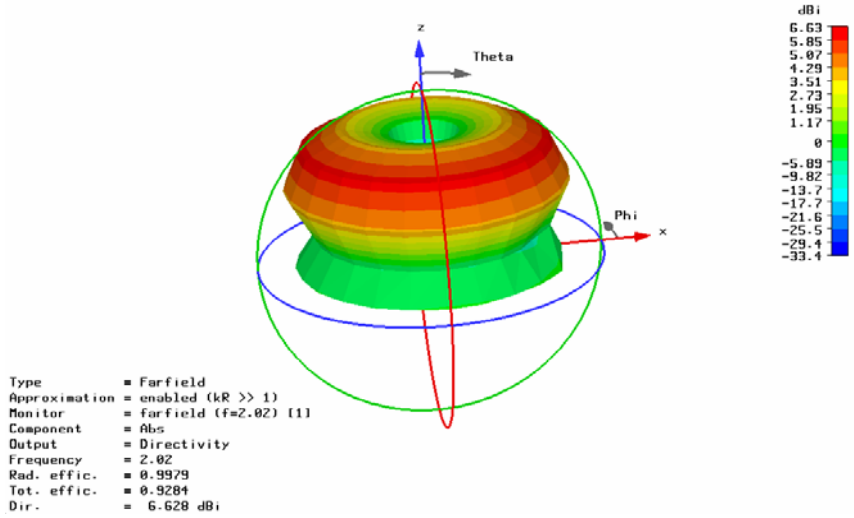
- Length = 10.6 cm (resonant at 2.0 GHz)
- Distance between antennas = 100 cm
- No enclosure



Isolated Monopole Antenna (2 GHz)



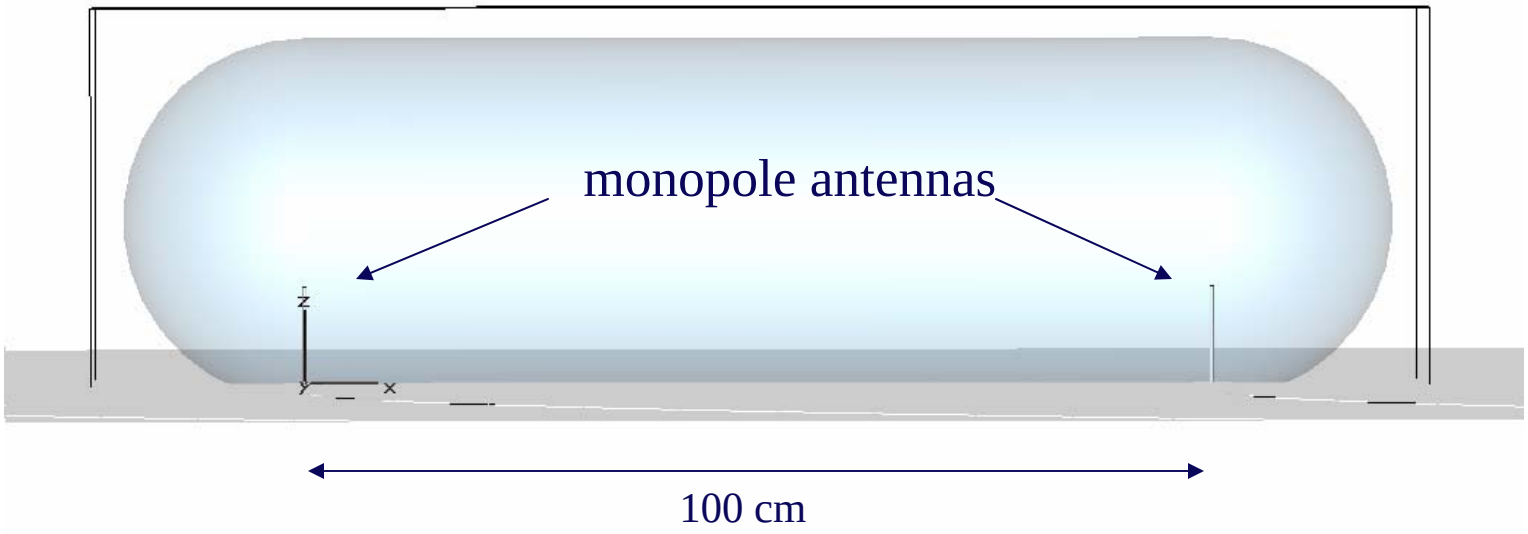
Return loss (S_{11}) as a function of frequency for one of the monopole antennas. The 10 dB bandwidth is close to 100 MHz (5%), which is typical for monopole antennas.



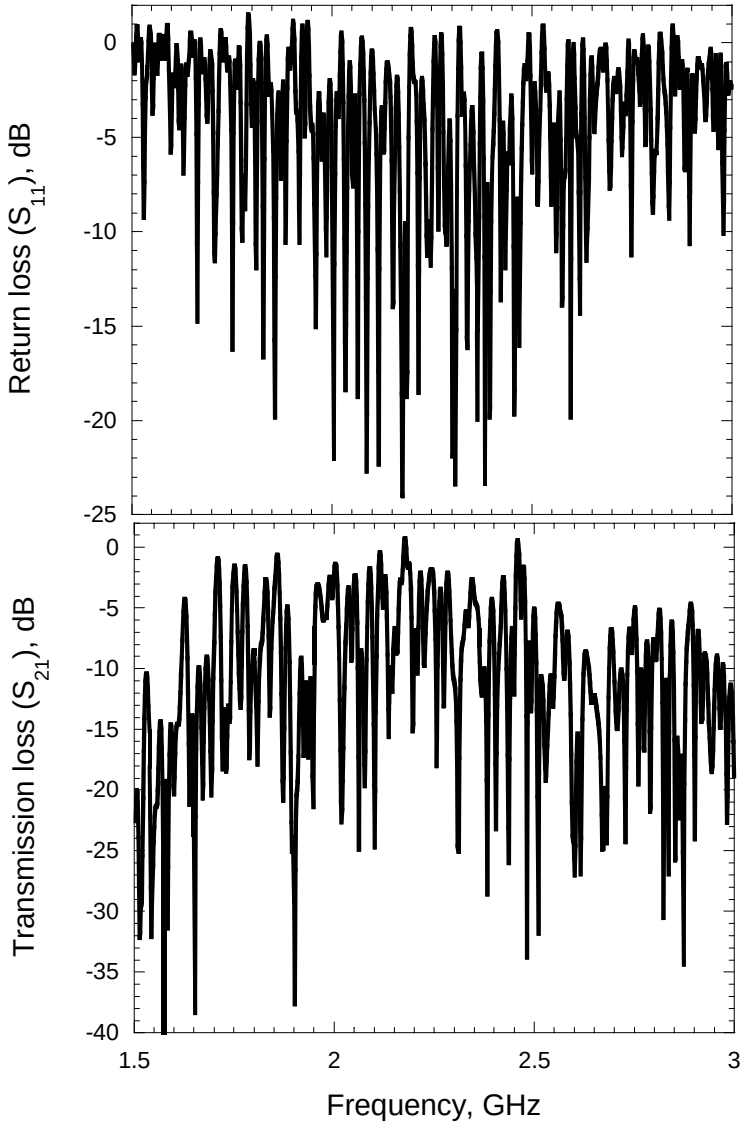
Radiation pattern of one of the monople antennas.

Coupled monopole antennas, enclosed in cylindrical metal cavity

- Monople length = 10.6 cm (resonant at 2.0 GHz)
- Distance between antennas = 100 cm
- Cylindrical metal enclosure, radius = 20 cm
- Interior of enclosure is air



2 GHz coupled monopole antennas, enclosed in cylindrical metal cavity

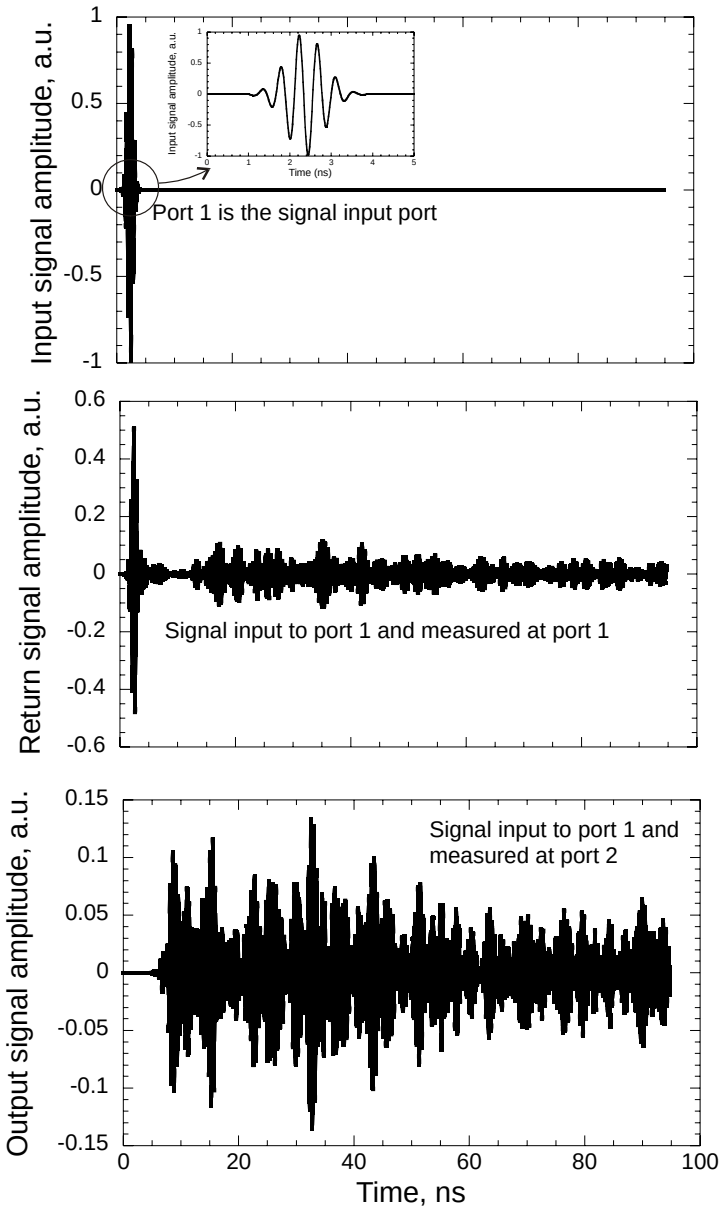


- Return loss (S_{11}) for one of the monopole antennas, and transmission loss (S_{21}) for the link between the pair of monopole antennas.

- The pair of antennas are enclosed in a metal cylinder.

- The large number of S_{11} minima and corresponding S_{21} maxima are probably due to multiple reflections from the enclosure walls.

2 GHz coupled monopole antennas, enclosed in cylindrical metal cavity (continued)

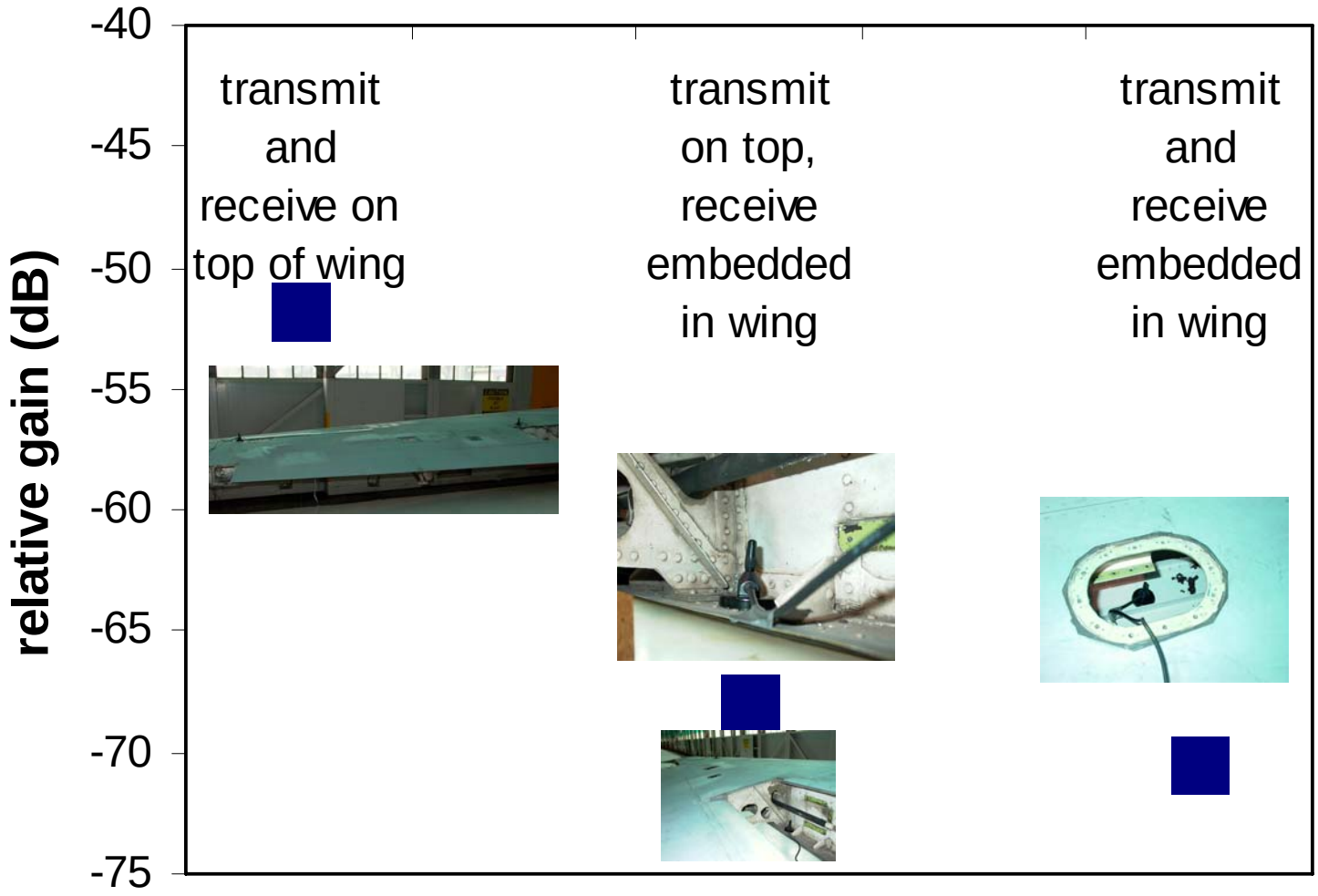


- Simulation performed using Microwave Studio's transient solver.
- Gaussian input signal, with frequency components covering the 1.5 – 3.0 GHz range.
- Reverberations clearly present in the port 1 and port 2 received signal spectra. These are attributed to reflections from the metallic walls of the cavity.

2.4 GHz monopole (S01-011)

Distance between transmit and receive antennas = 208 cm

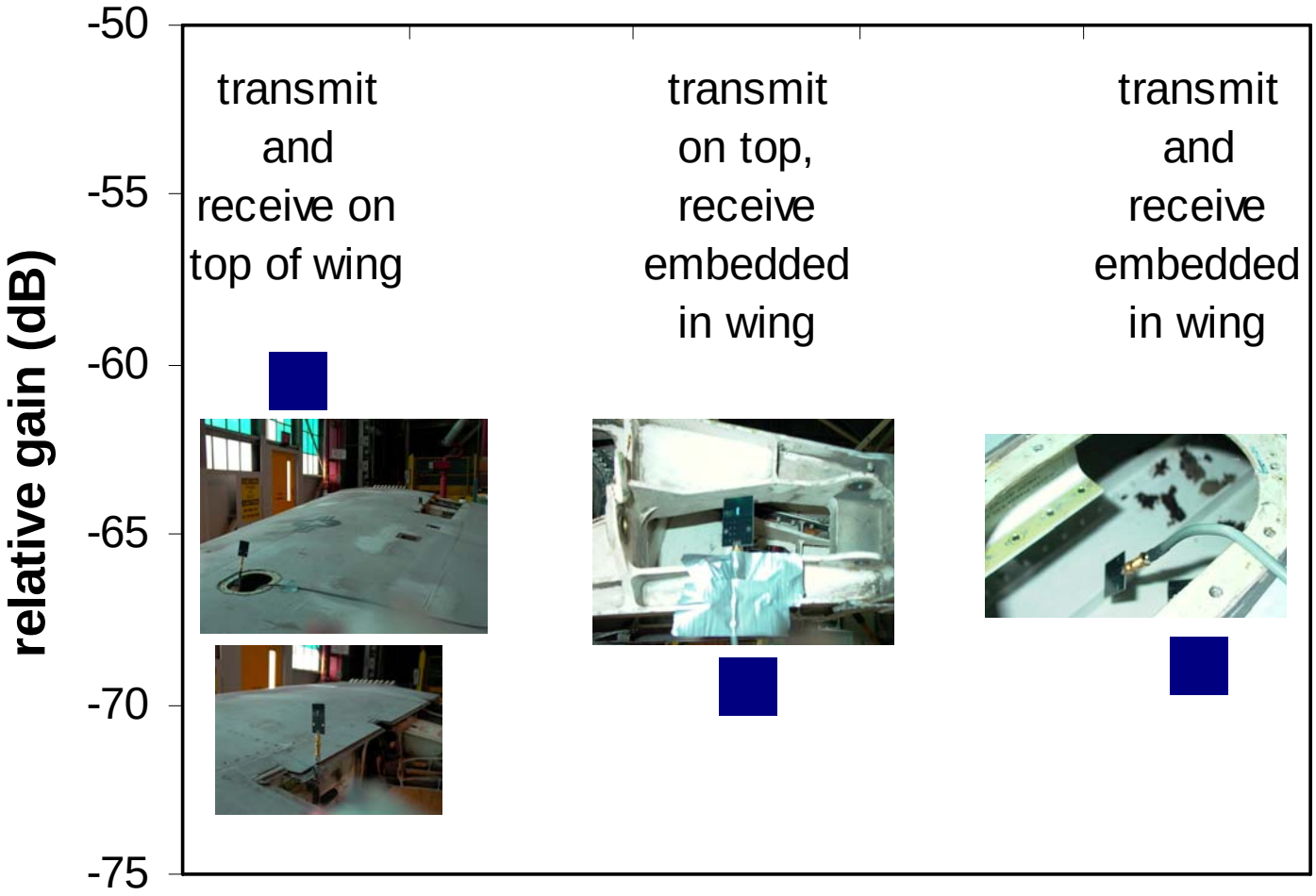
RF input power = 0 dBm



2.4 GHz Ceramic Antennas

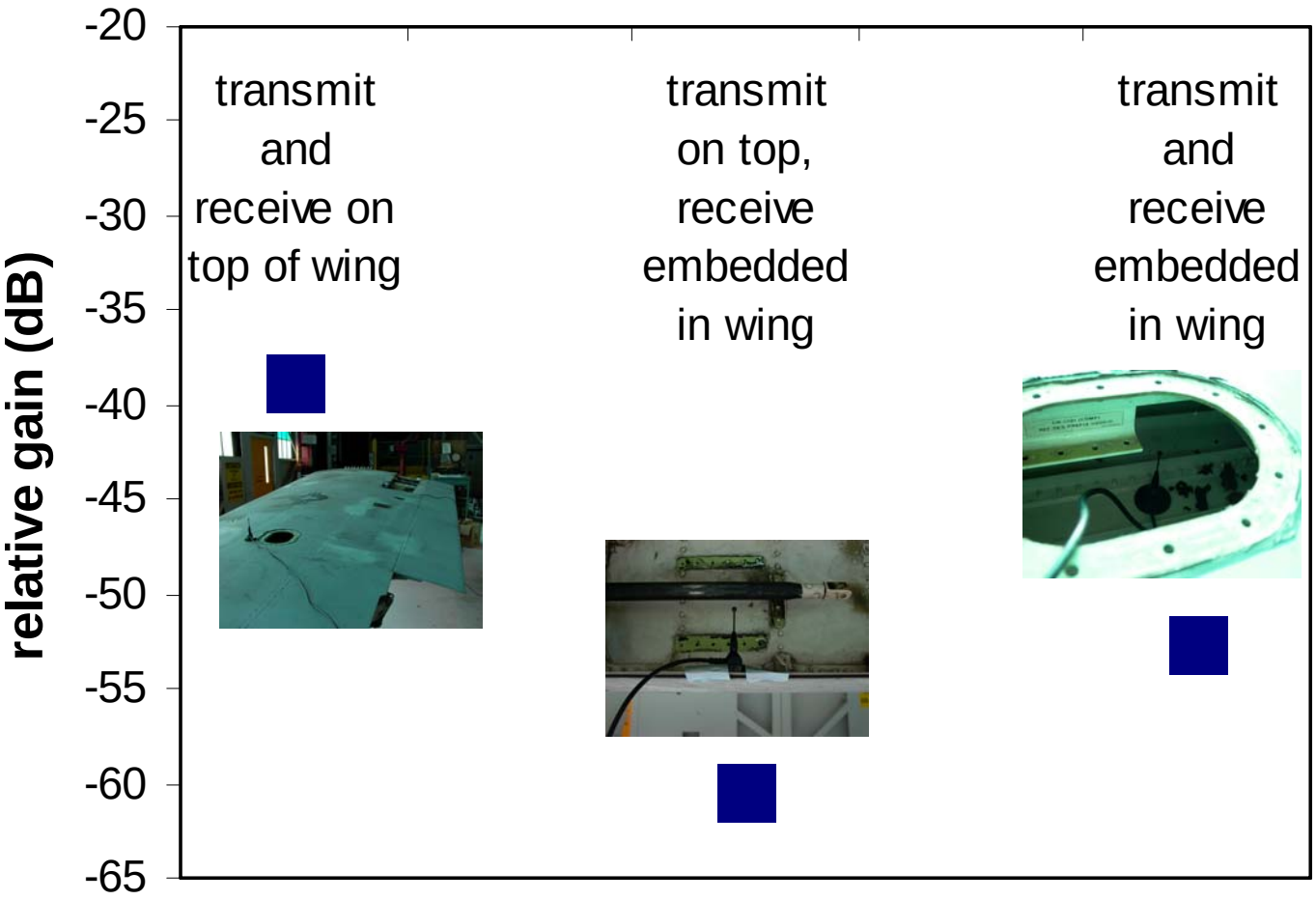
Distance between transmit and receive antennas = 208 cm

RF input power = 0 dBm



900 MHz monopole (S01-010)

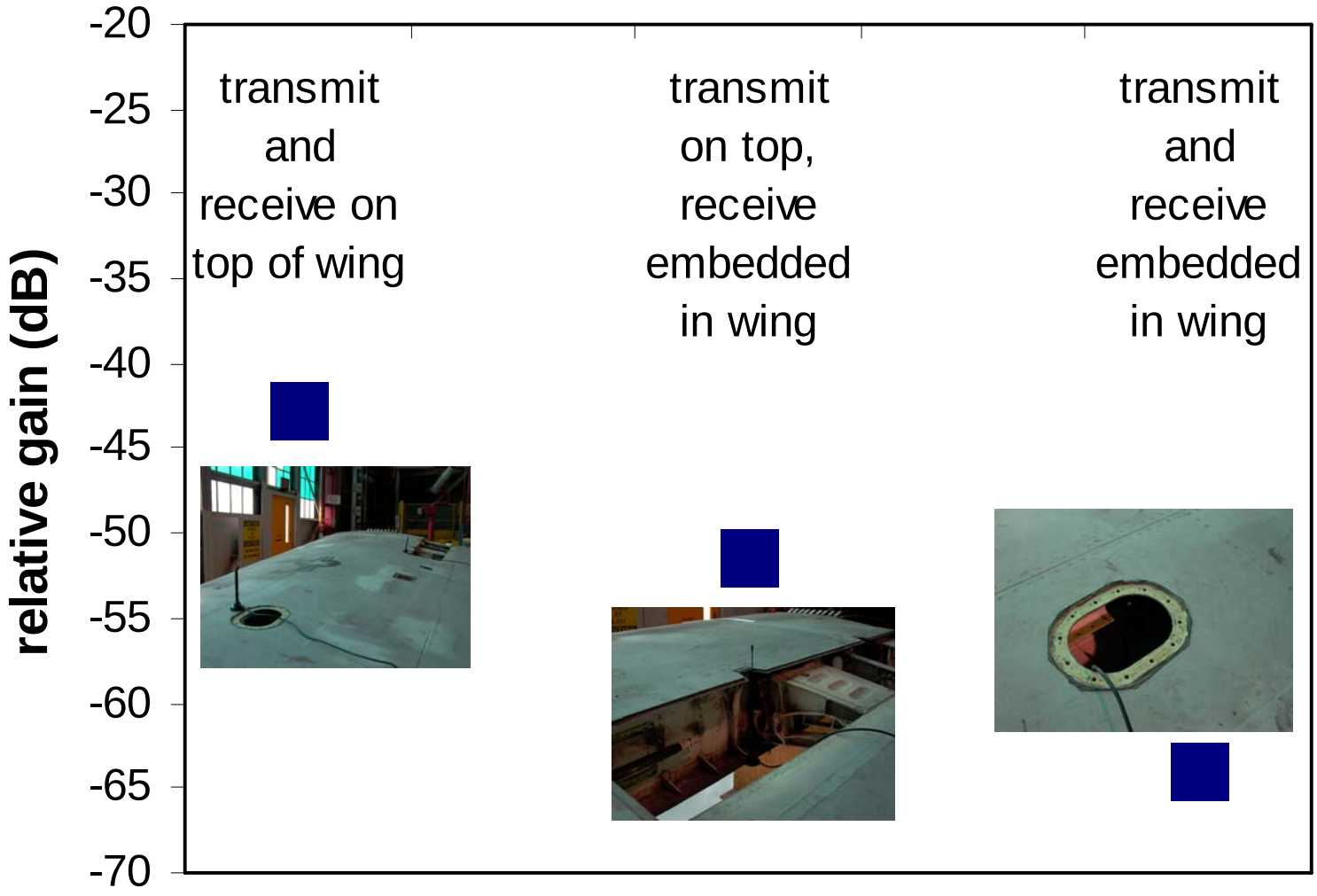
Distance between transmit and receive antennas = 208 cm
RF input power = 0 dBm



900 MHz monopole (S01-006)

Distance between transmit and receive antennas = 208 cm

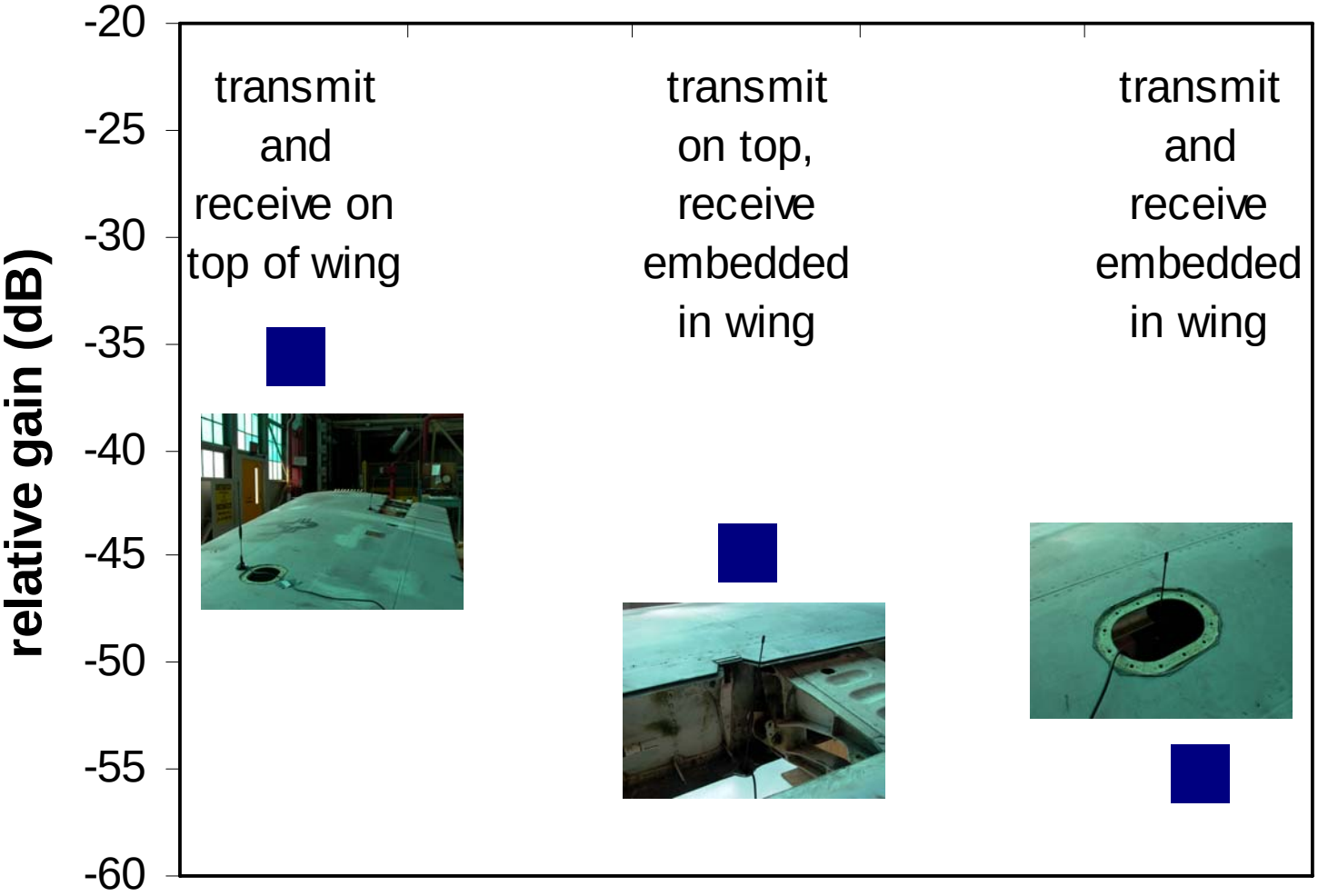
RF input power = 0 dBm



900 MHz monopole (S01-008)

Distance between transmit and receive antennas = 208 cm

RF input power = 0 dBm



Conclusions

•For low data rates (1 ksps), RF communications links are feasible with low power transmitter (approximately -20 dBm).

-Communication links are possible even if there is no direct line-of-sight between the transmitter and receiver.

•For higher data rates (1 Msps), RF communication links are feasible, but require higher transmit powers.

-10 dB increase in bandwidth requires 10 dB increase in transmit power.

•For the highest data rates tested (10 Msps), RF communication links were not possible unless there was a line-of-sight pathway between the transmit and receive antennas.

-Simulations suggest that multi-path reflections may contribute to unacceptably high error vector readings when there was no line-of-sight pathway.

•Propagation losses were lower for the 900 MHz link than the 2.4 GHz link.

-Suggests that if spectrum issues were not a concern, lower frequency RF links would be preferred.

-However, spectrum issues are a major concern.

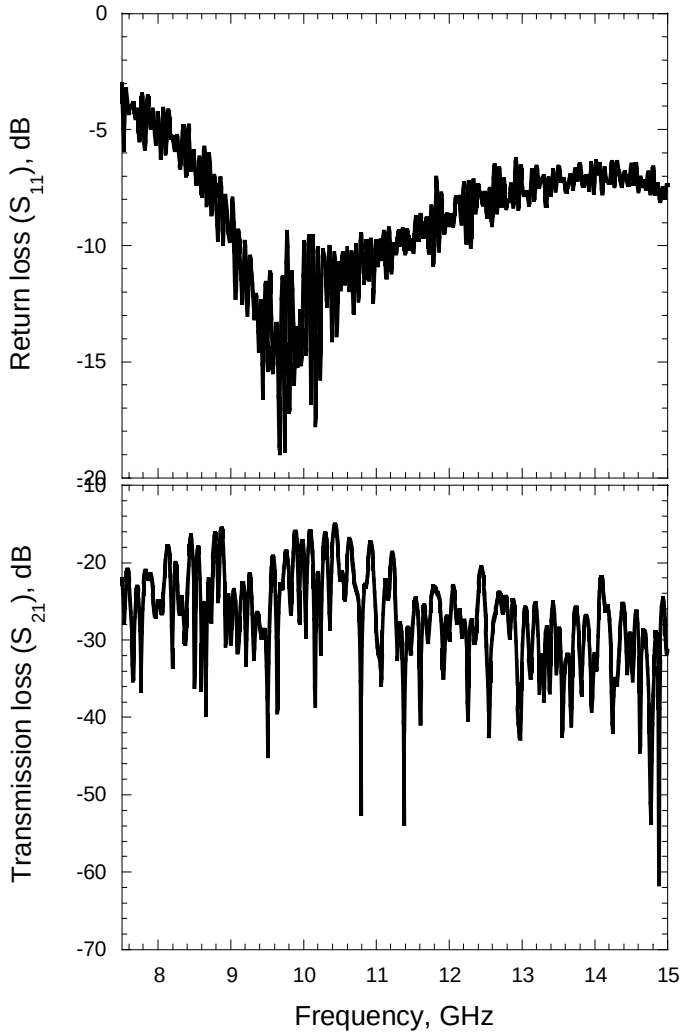
•Based on current data, tentative recommendations for high data rate RF communication links are:

•Minimize RF power (-10 to 0 dBm range).

•Lowest frequency with available spectrum and free from excessive interference.

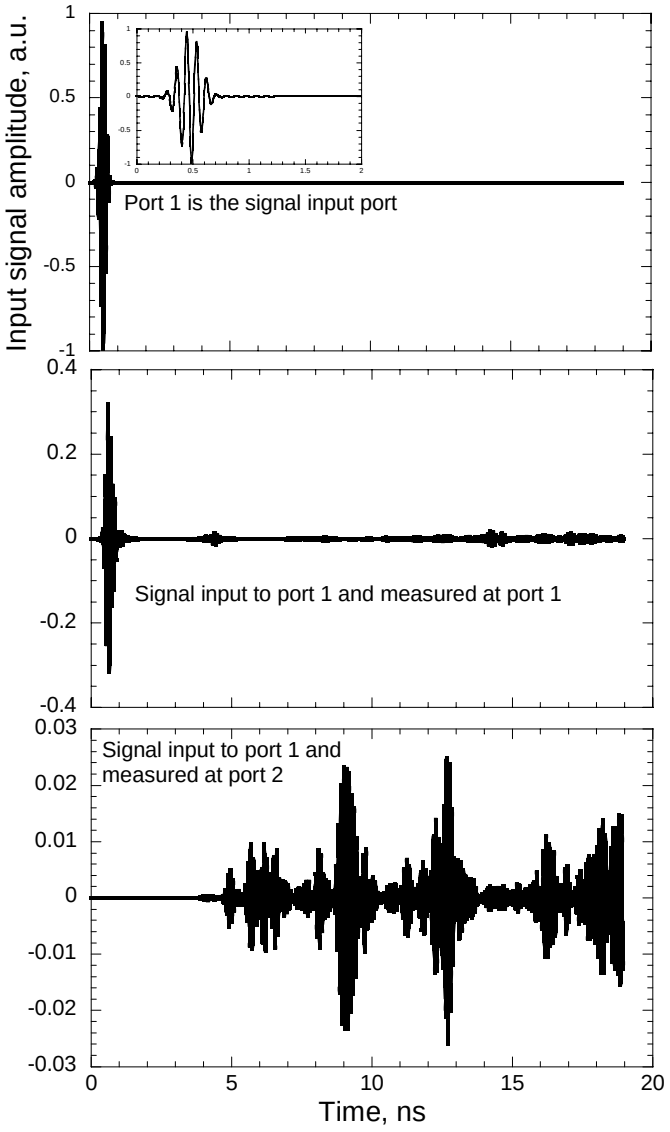
•Place RF communication modules so there is a line-of-sight pathway.

10 GHz coupled monopole antennas, enclosed in cylindrical metal cavity (continued)



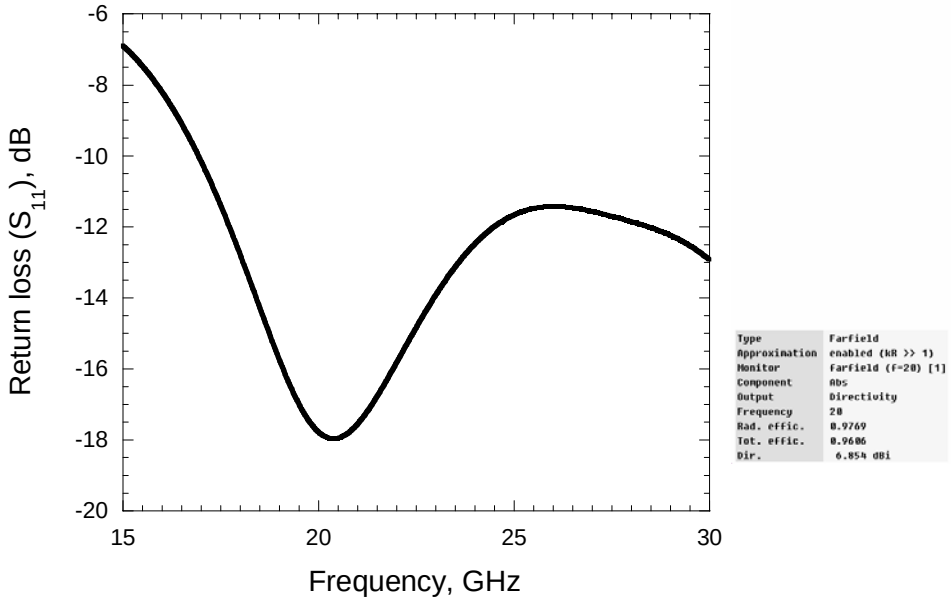
- Return loss spectrum resembles that of an isolated antenna, although considerable reverberation effect is evident.

10 GHz coupled monopole antennas, enclosed in cylindrical metal cavity (continued)

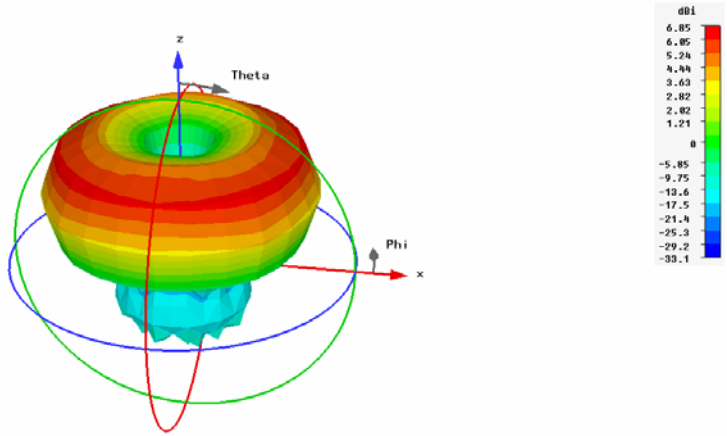


- The time need to travel 100 cm (from the input to the output antenna) is 3.3 nanoseconds.
- The time needed to travel from the transmit antenna, reflect from the far wall, and return to the transmit antenna is about 8 nsec.

Isolated Monopole Antenna (20 GHz)

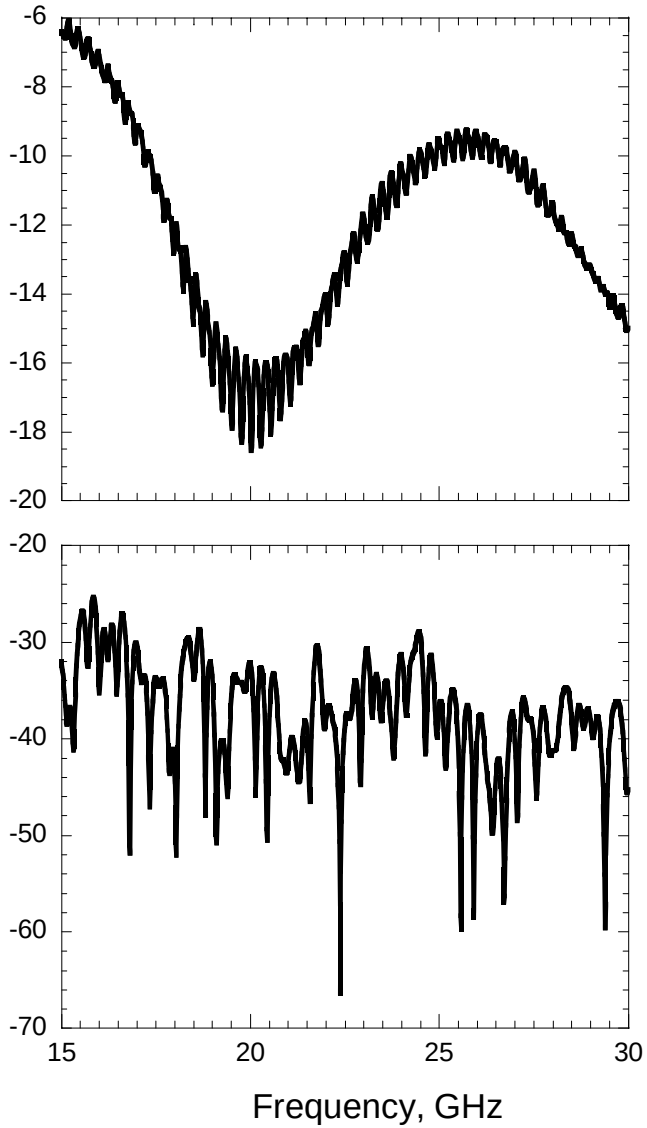


Return loss (S_{11}) as a function of frequency for one of the monopole antennas.

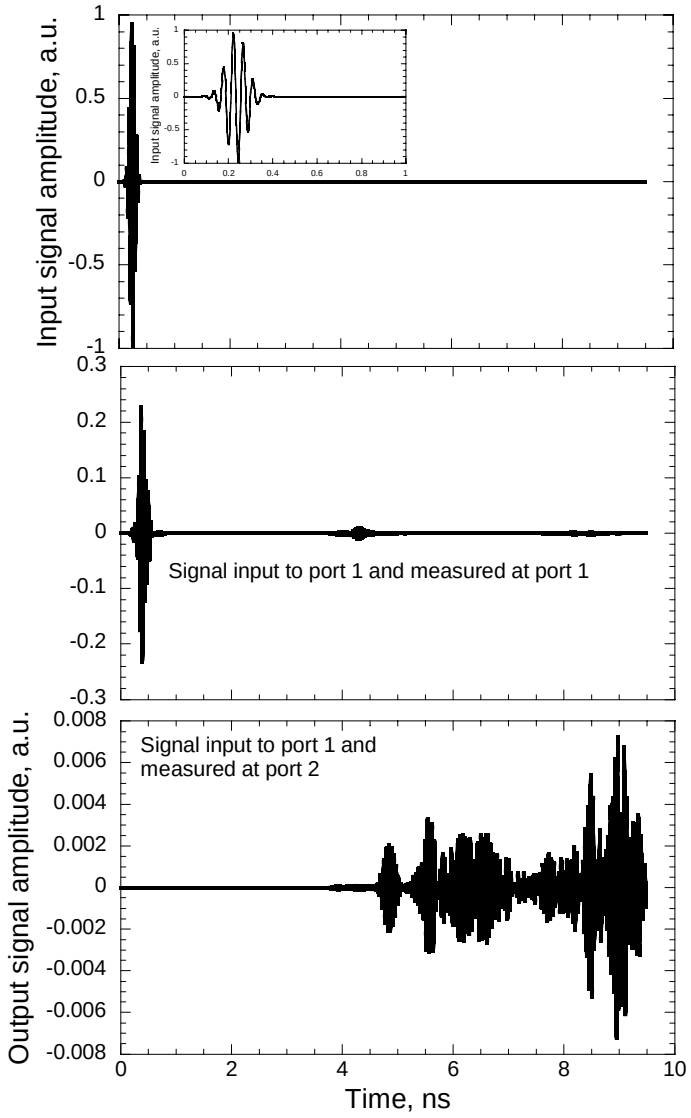


Radiation pattern of one of the monople antennas.

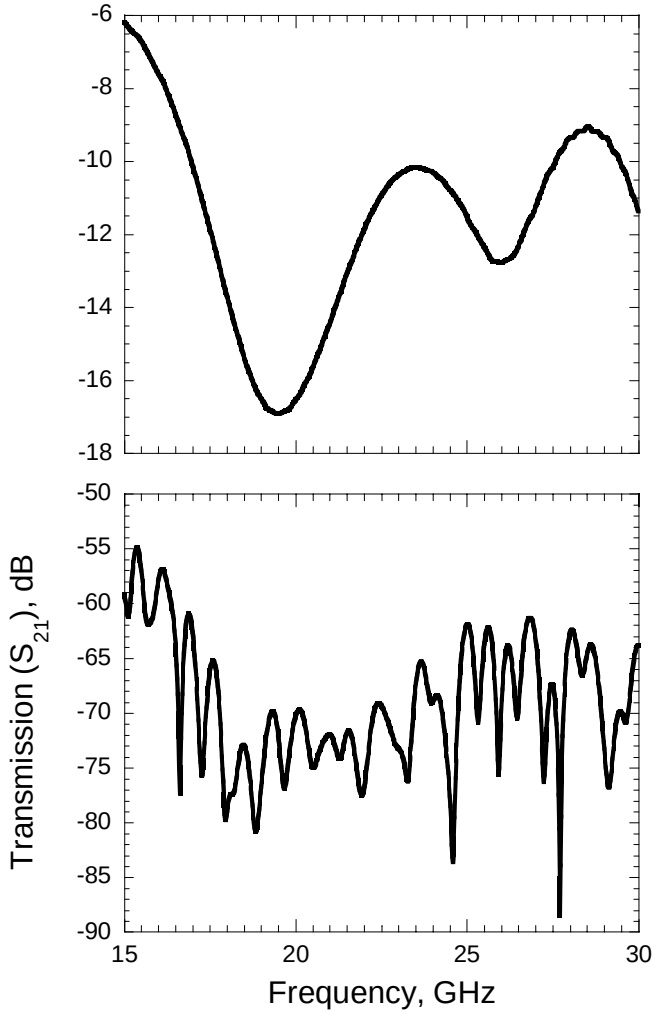
20 GHz coupled monopole antennas, enclosed in cylindrical metal cavity (continued)



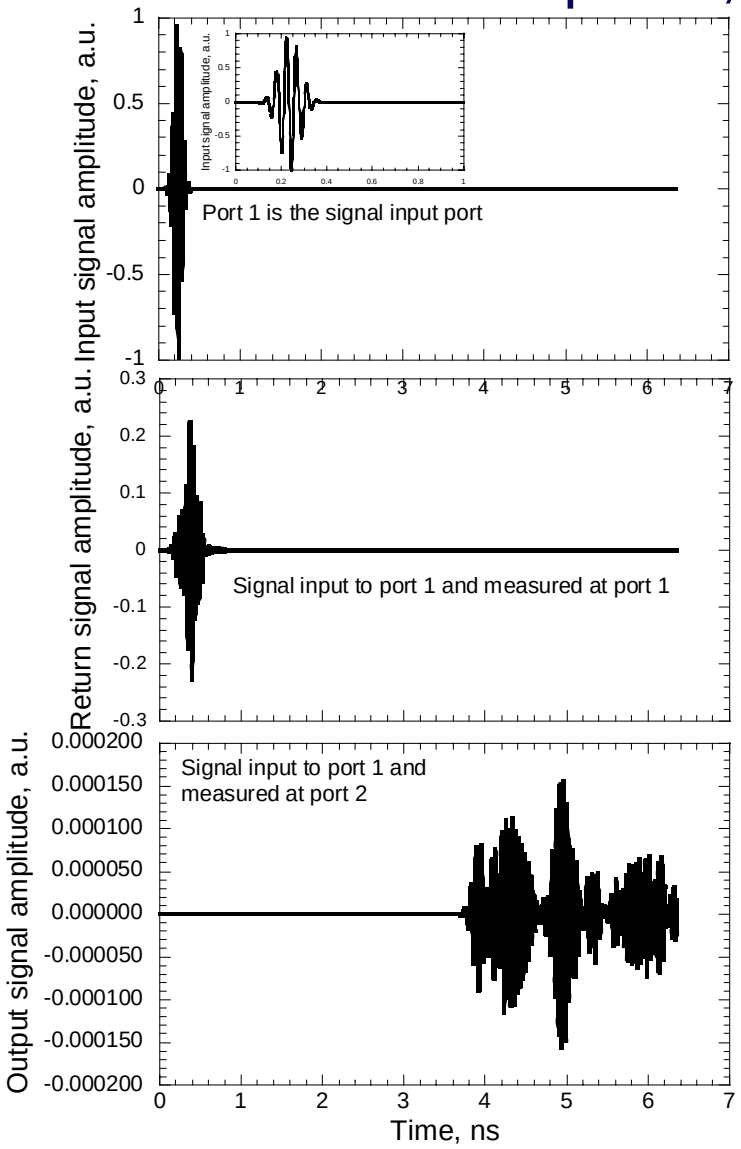
20 GHz coupled monopole antennas, enclosed in cylindrical metal cavity (continued)



20 GHz coupled monopole antennas, metal ground plane, enclosed in air

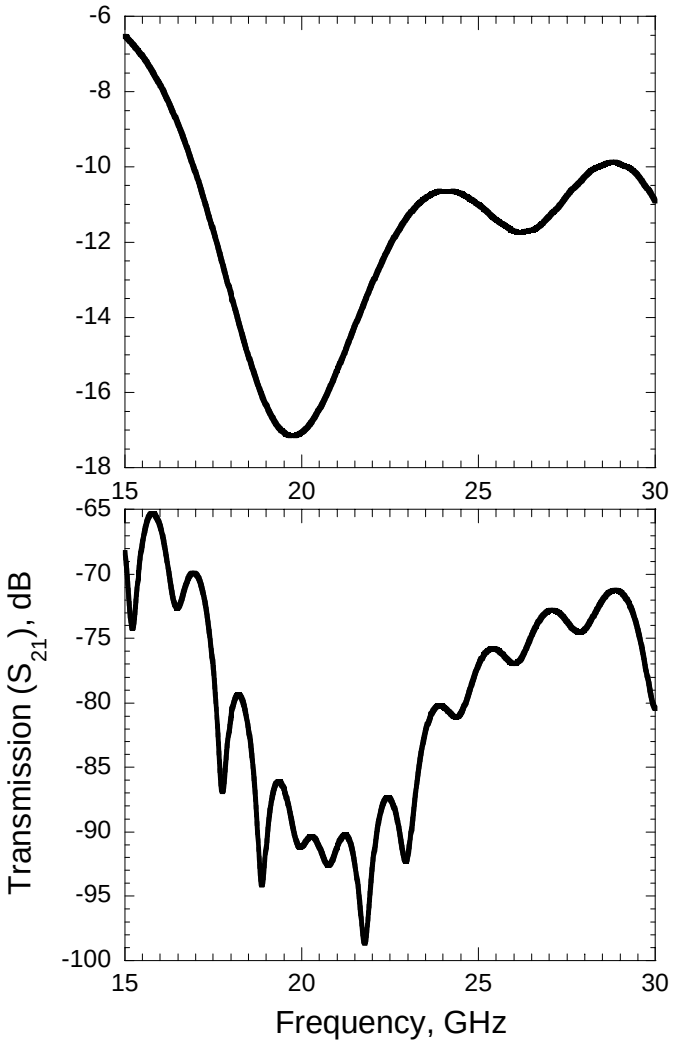


20 GHz coupled monopole antennas, metal ground plane, enclosed in air



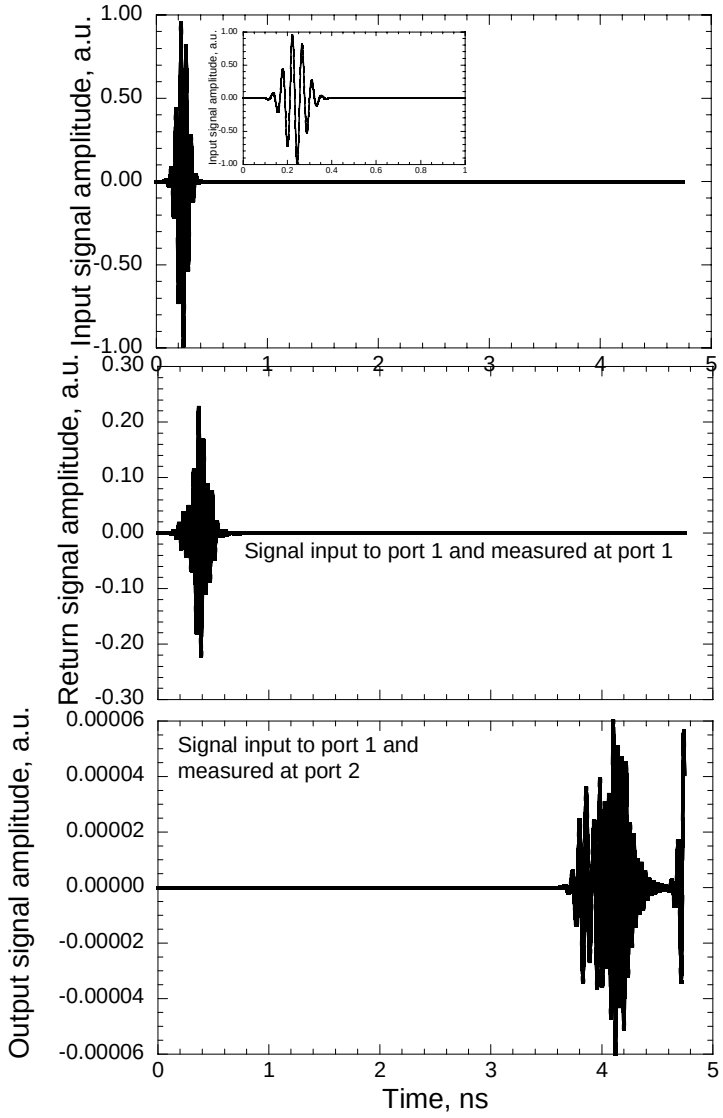
- The time scale is only long enough to show one-way transmission from transmit to receive antennas.
- Input pulse spreads considerably by the time it reaches the receive antenna.
- Initial data suggests that modulation techniques that are resilient to multipath effects will be most useful for this application.

20 GHz coupled monopole antennas, completely enclosed in air



- Coupling between transmit and receive antennas is lowest when the antennas are completely surrounded by air (perfectly absorbing background).
- I had expected a peak in transmission at the frequency where the two antennas are resonant (20 GHz), but no peak is observed. This is something we need to understand.

20 GHz coupled monopole antennas, completely enclosed in air)



- The presence of metal (either as a ground plane for both antennas, or an enclosure that totally surrounds the antennas), increases transmission, but severely distorts the input signal.