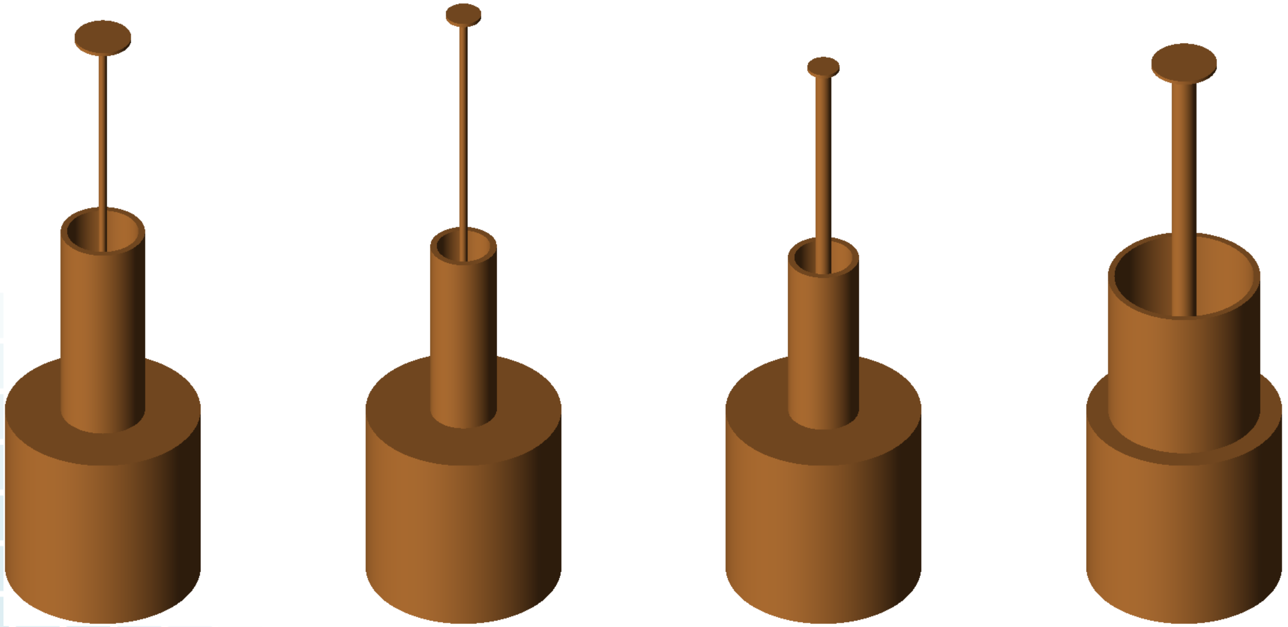
Design Optimization with XFdtd® EM Simulation Software Using GPU Acceleration and Particle Swarm Optimization

Broadband Antenna for Use Over Varying Ground Conditions



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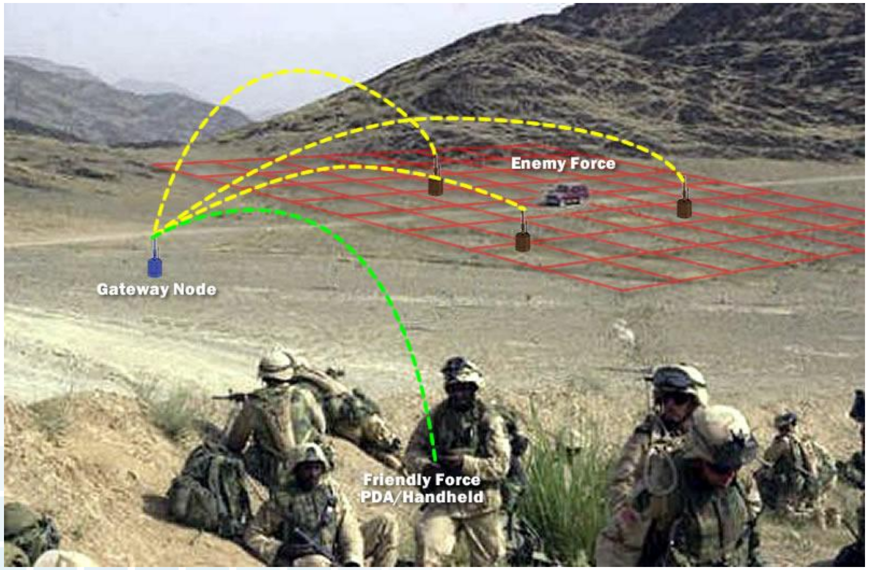
Introduction

- Devices designed for free space operation often fail to meet expectations when deployed in their actual environment.
- We will consider the example of designing a broadband antenna for an unattended ground sensor.
- We'll use several features in Remcom's XFdtd Release 7 (XF7) to generate and evaluate potential designs:
  - Particle Swarm Optimization (PSO)
  - Full wave 3D FDTD solver
  - XStream® GPU Acceleration

Unattended Ground Sensor

- Small, cylindrical sensor
  - 23 cm tall
  - 7.6 cm radius

Unattended Ground Sensor



- Communicates with other nearby sensors as part of a mesh network

Design Goals

- Broadband operation:
  - 225 MHz - 500 MHz
  - Return loss <= -10 dB
- Uniform pattern in the horizontal plane (< 3 dBi variation)
- High gain (>= 5 dBi)
- Near constant gain over bandwidth
- Preference for low-profile solution
- Function over a variety of ground conditions

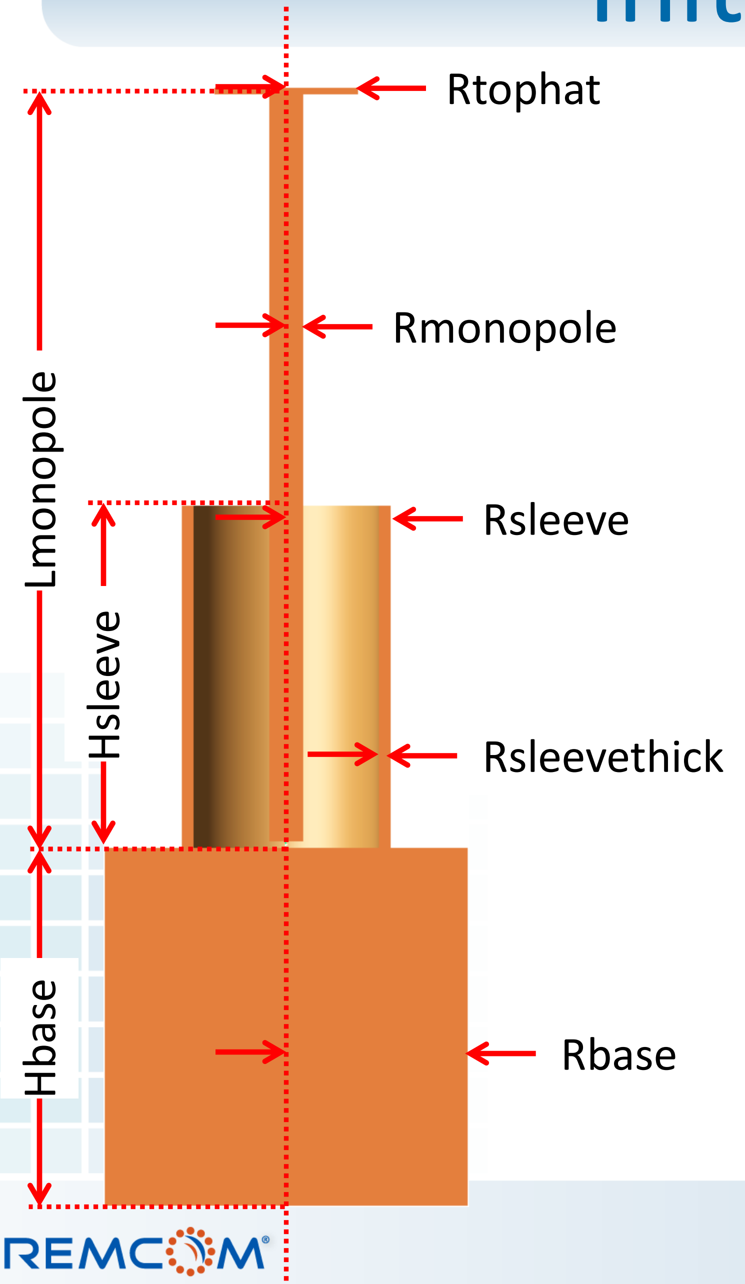
Benefits of Simulation

- Repeatedly building prototypes is prohibitively expensive and time consuming.
- The measurement environment includes specific ground conditions that are difficult or impossible to reproduce between measurements.
- This can make it impossible to reliably judge the impact of design modifications.
- Simulation removes this uncertainty from the antenna design process.

Antenna Choice

- Several broadband antenna choices were considered.
- The broadband sleeve monopole (BBSM) was chosen for performance and size characteristics.
- For the sake of this study, all materials are considered to be perfectly conducting metal.
- Each dimension of the antenna design is defined as a parameter in the software to allow a variety of designs to be simulated.

Initial Design

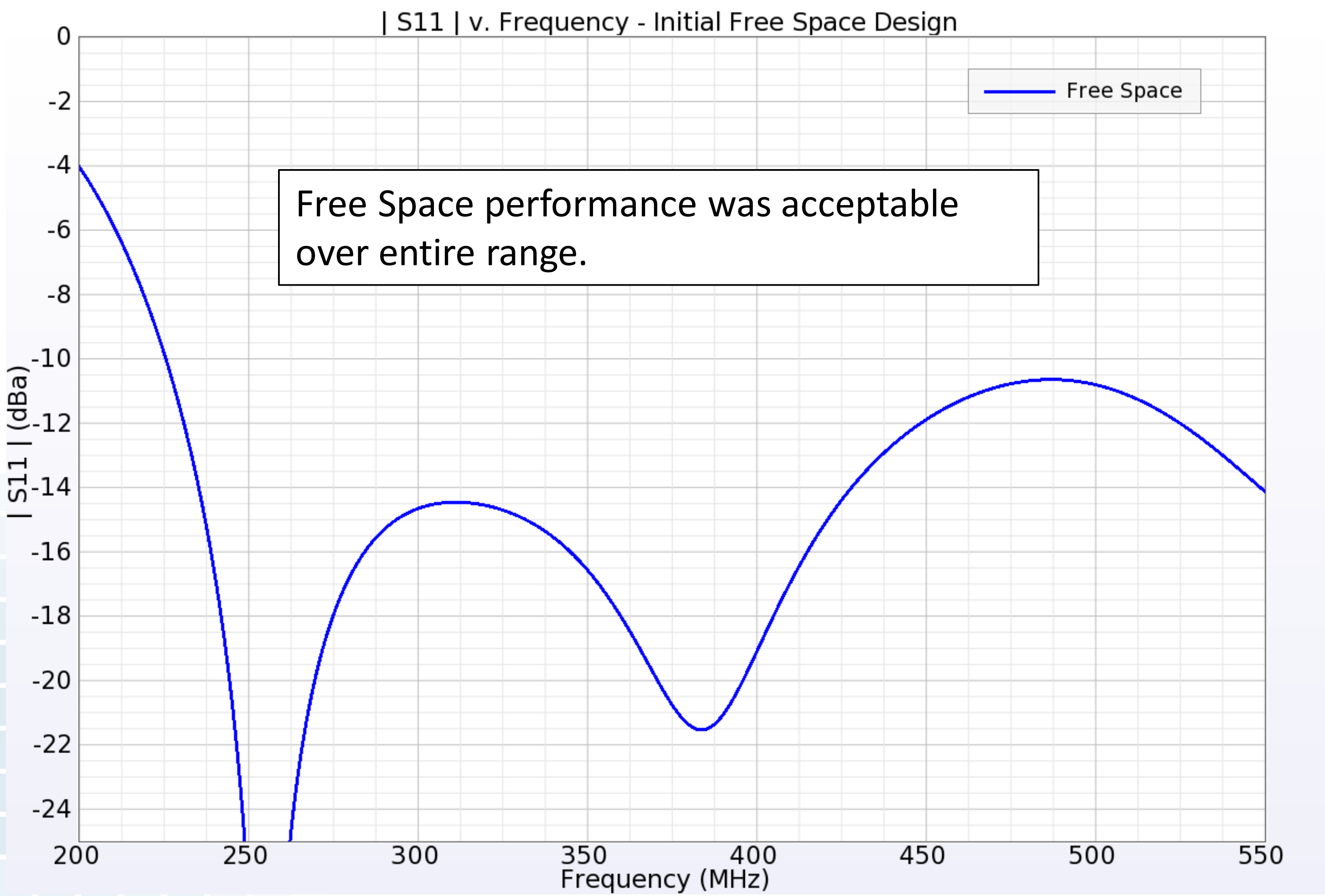


Parameter	Value (cm)
Lmonopole	31.3
Rmonopole	1.0
Hsleeve	13.0
Rsleeve	5.2
Rtophat	2.5
Rbase	7.6
Hbase	15.0
Htophat	0.3
Rsleevethick	0.5

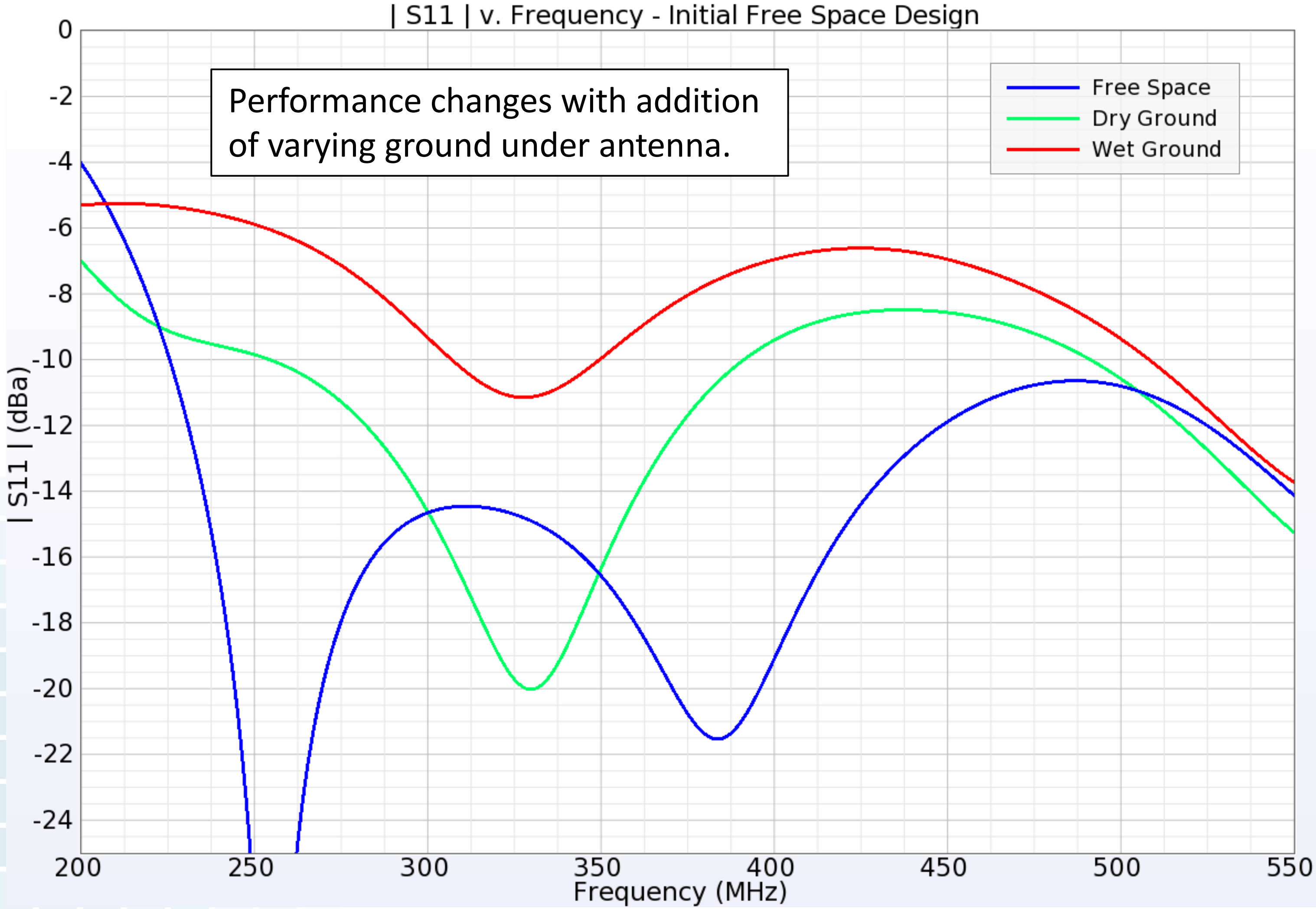
Initial Performance

- The performance of this antenna design is quite good in free space.
- When the antenna is placed over dry ground the antenna does not operate well over the upper part of the frequency range.
- Over wet ground, the antenna does not operate over most of the range.

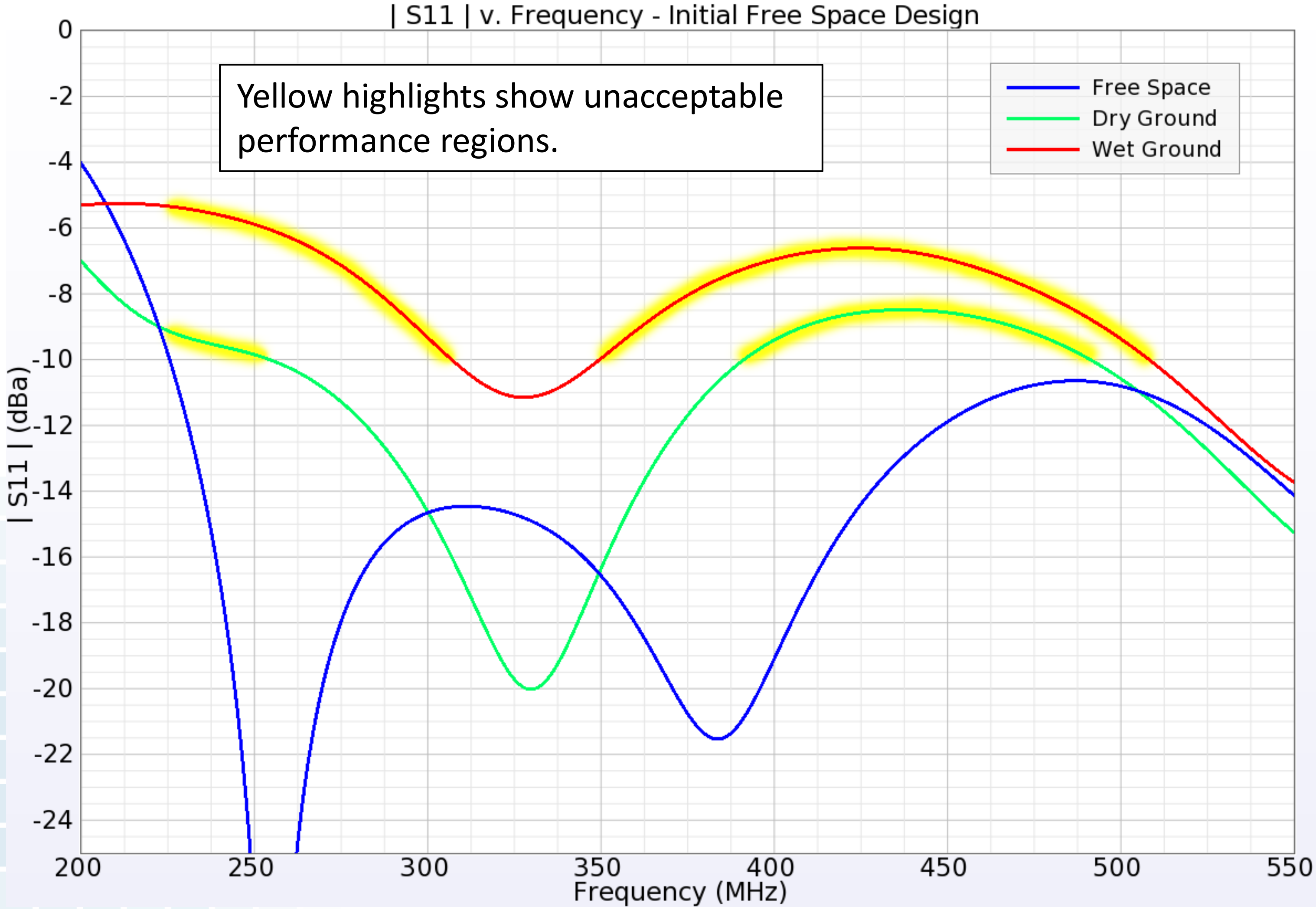
Performance



Performance



Performance



What Now?

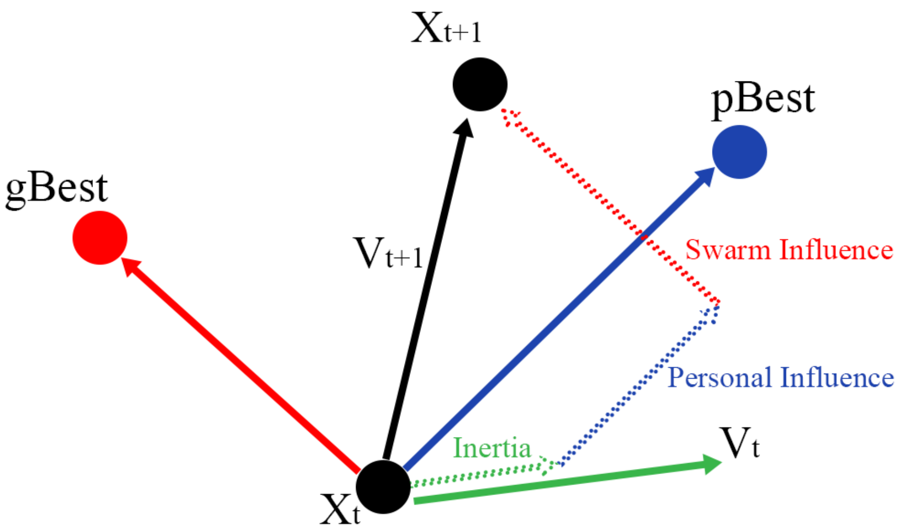
- Parameter sweep is impractical.
  - We do not know how the parameters interrelate.
- Try a global optimization technique.
  - Allows for design by specifying a target goal
  - Does not require knowledge of parameter dependencies
  - Can be run as a background or asynchronous process

Particle Swarm Optimization (PSO)

- Originally presented by Kennedy and Eberhart
- Iterative, stochastic optimization technique
- Inspired by the social behavior observed in nature
  - Flocks of birds
  - Schools of fish
  - Swarms of insects
- Each particle represents a potential solution described by its position in the space.
- The suitability of the solution is determined by evaluating a fitness function.

Particle Swarm Optimization (PSO)

- Particles scattered throughout the solution space
- At the start of an iteration, each particle chooses a new position based on its current position and an updated velocity.
- Particle velocity updated as a function of:
  - Personal best
  - Global best seen by swarm
  - Previous velocity
- Process repeated for many iterations (generations)

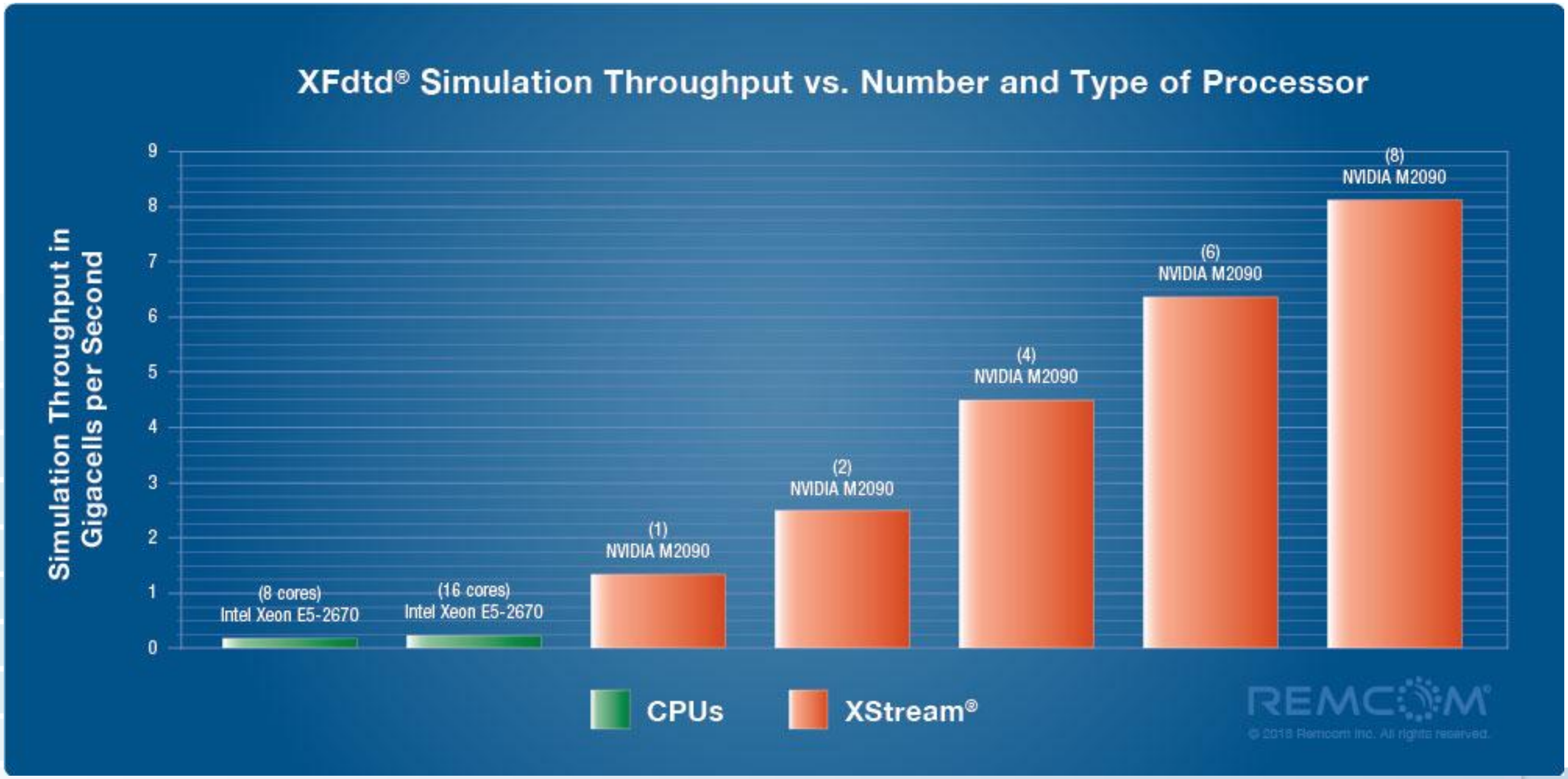


Computational Needs

- Particle Swarm Optimization can require hundreds or thousands of iterations to converge on best values.
- Each simulation can take a significant amount of time (minutes to hours), so high performance computing is required.
- Needs are met by using Remcom's XStream® GPU Acceleration.

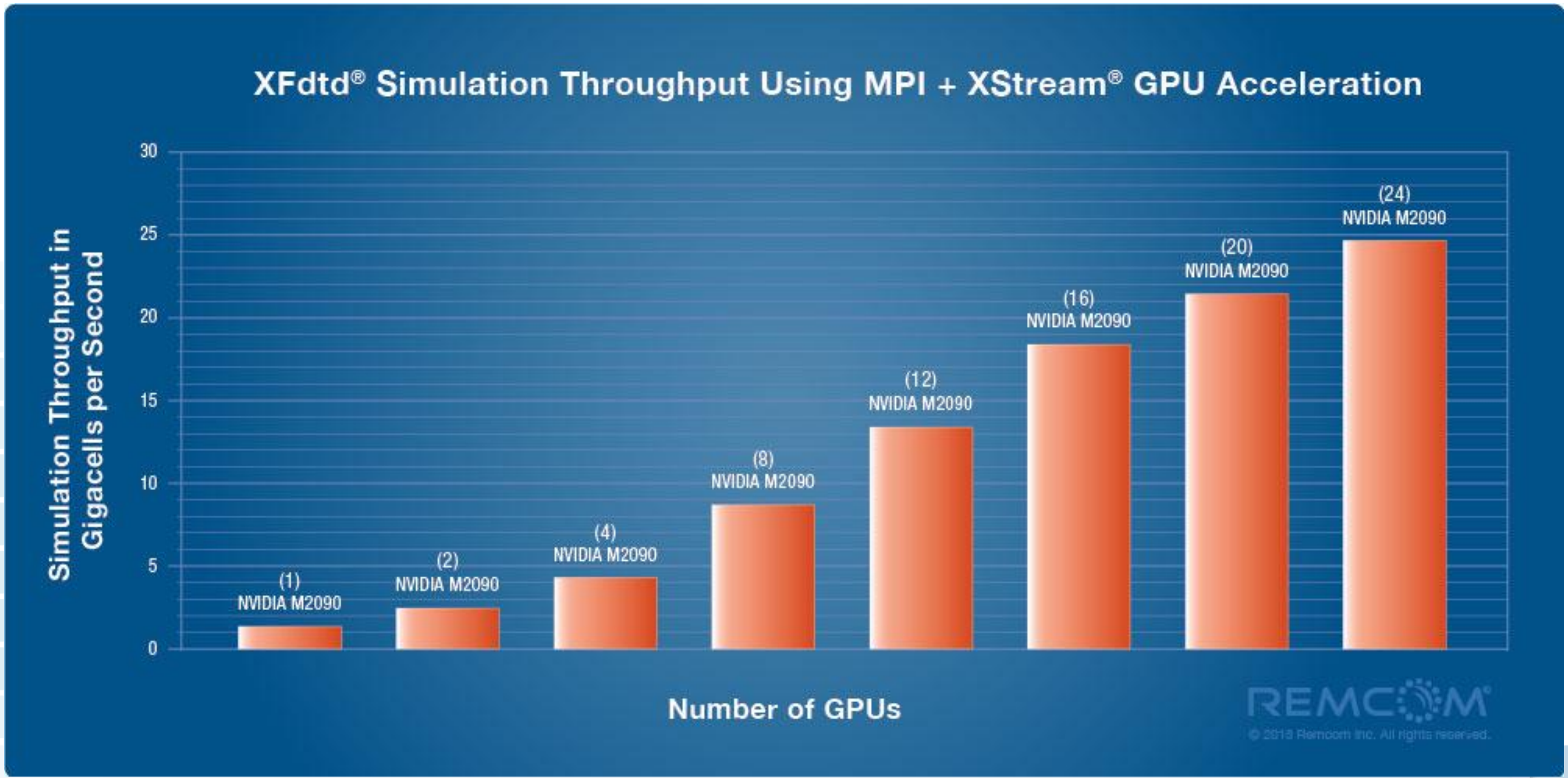
XStream GPU Acceleration

- Massively parallelized implementation
- Powered by NVIDIA's CUDA architecture
- Up to hundreds of times faster than a CPU



MPI + XStream

- For very large problems, one GPU node may not have enough memory.
- MPI + XStream allows a problem to be split among GPUs in multiple systems.



PSO Execution

- Optimizations performed on a loose cluster of machines at Remcom
  - Machines physically distributed throughout office
  - Each has a variable number of C2050 or C2075 GPUs
  - Connected via gigabit Ethernet
  - 10 - 12 GPUs available over the course of this work
- Simulations handled by a queuing system which executed each job on a single GPU
  - Best approach for maximum throughput
  - No communication required between machines

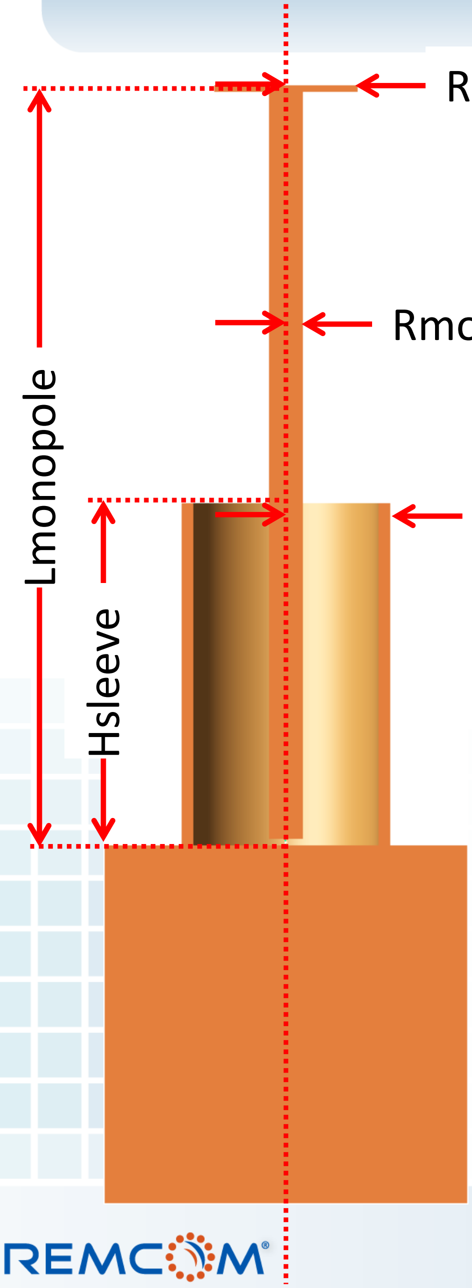
Antenna Design Using PSO

- Use the random nature of the PSO to generate multiple designs.
- This can be achieved by executing multiple independent optimizations.
- Focus on the wet ground environment, because it seems to be the most difficult.
- Investigate the performance of these designs in varying environments.

PSO Setup

- Focused optimization on five antenna parameters over selected bounds
- Performed five separate optimizations to generate multiple designs
- Chose to use 12 particles in the PSO and permitted each to run up to 200 generations

PSO Setup



Parameter	Min (cm)	Max (cm)
Lmonopole	20.0	40.0
Rmonopole	0.25	1.0
Hsleeve	5.0	19.0
Rsleeve	2.0	7.0
Rtophat	1.0	5.0

- Five Optimizations
  - 12 Particles
  - 200 Generations

Initial PSO Results

- Unfortunately, no valid design was reached during the initial five optimizations.
- Performed additional five optimizations with 18 particles, each able to reach 600 generations

Optimization Results

Lmonopole (cm)	Rmonopole (cm)	Hsleeve (cm)	Rsleeve (cm)	Rtophat (cm)	Min Frequency (MHz)	Max Frequency (MHz)
26.35	0.3	17.81	2	5	240.3	502.5
26.36	0.3	17.85	2	5	240.3	502.5
26.5	0.3	17.92	2	5	240.3	501.5
26.71	0.3	17.9	2.01	5	240.6	499.7
26.9	0.31	17.84	2.04	5	240.7	500.1
27.96	0.32	18.03	2.12	5	240.8	498.7
26.2	0.3	17.7	2	5	240.8	504.4
26.39	0.3	17.83	2.01	5	240.8	503.0
26.21	0.3	17.87	2.01	4.99	242.0	504.0
38.38	0.35	17.07	2.51	1.05	258.8	488.8

None of the optimizations was able to find an answer that included the lower frequencies of the desired band.

Optimization Results

Lmonopole (cm)	Rmonopole (cm)	Hsleeve (cm)	Rsleeve (cm)	Rtophat (cm)	Min Frequency (MHz)	Max Frequency (MHz)
26.35	0.3	17.81	2	5	240.3	502.5
26.36	0.3	17.85	2	5	240.3	502.5
26.5	0.3	17.92	2	5	240.3	501.5
26.71	0.3	17.9	2.01	5	240.6	499.7
26.9	0.31	17.84	2.04	5	240.7	500.1
27.96	0.32	18.03	2.12	5	240.8	498.7
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26.21	0.3	17.87	2.01	4.99	242.0	504.0
38.38	0.35	17.07	2.51	1.05	258.8	488.8

- Optimization Timings:
  - Generation: 6.8 - 8.2 minutes
  - Total: 22.8 - 27.4 hours (12 particles, 200 generations)
  - Up to 120 hours for 18 particles and 600 generations

Conclusions of Initial Run

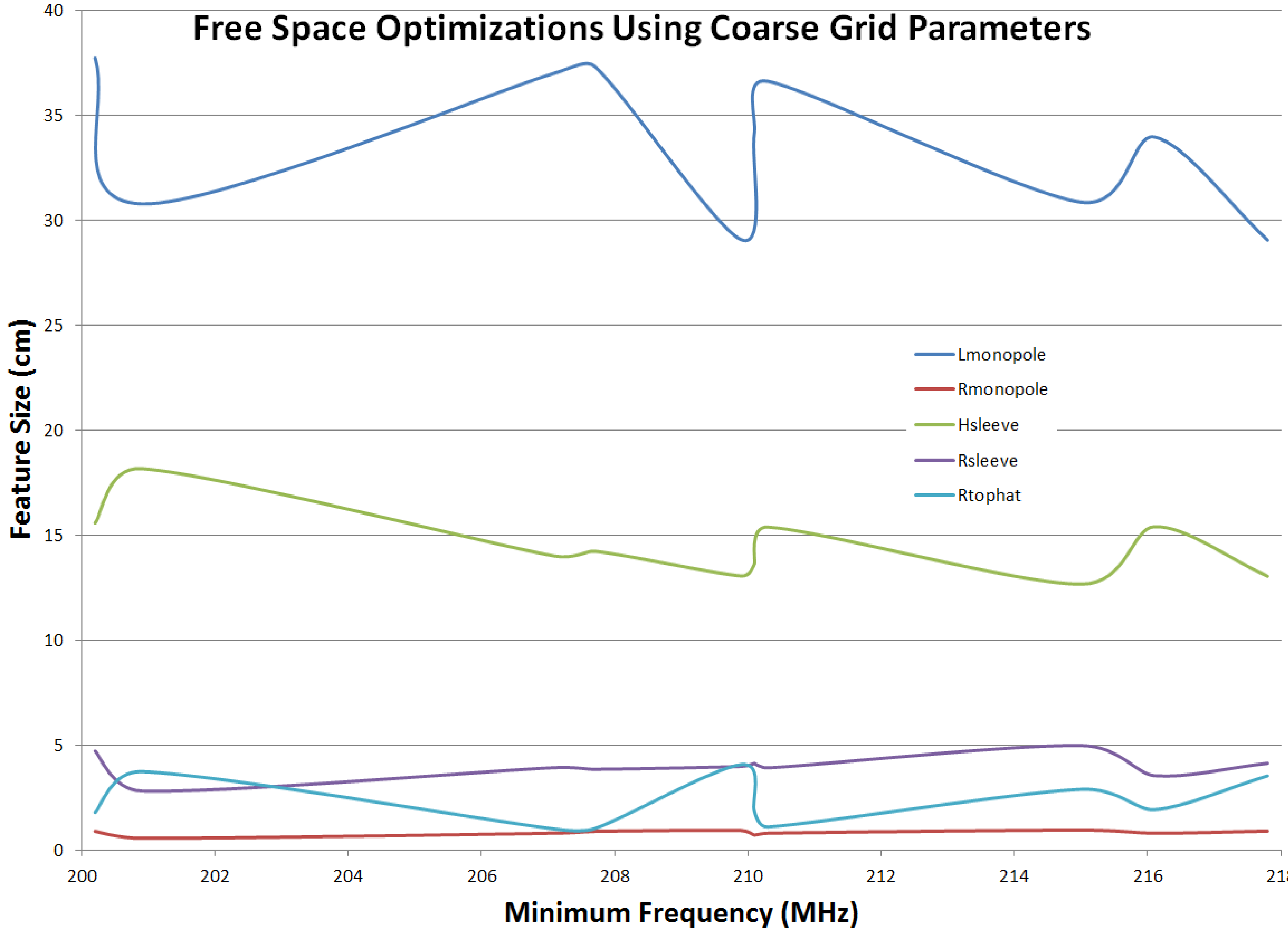
- PSO did not come up with a valid design despite numerous simulation runs.
- Simulations were very time-consuming, requiring many hours of computer time.
- Essentially no correct result was possible, so the algorithm spent a lot of time trying to fine-tune the best answer it could find.

What Next? Understanding Design Tradeoffs

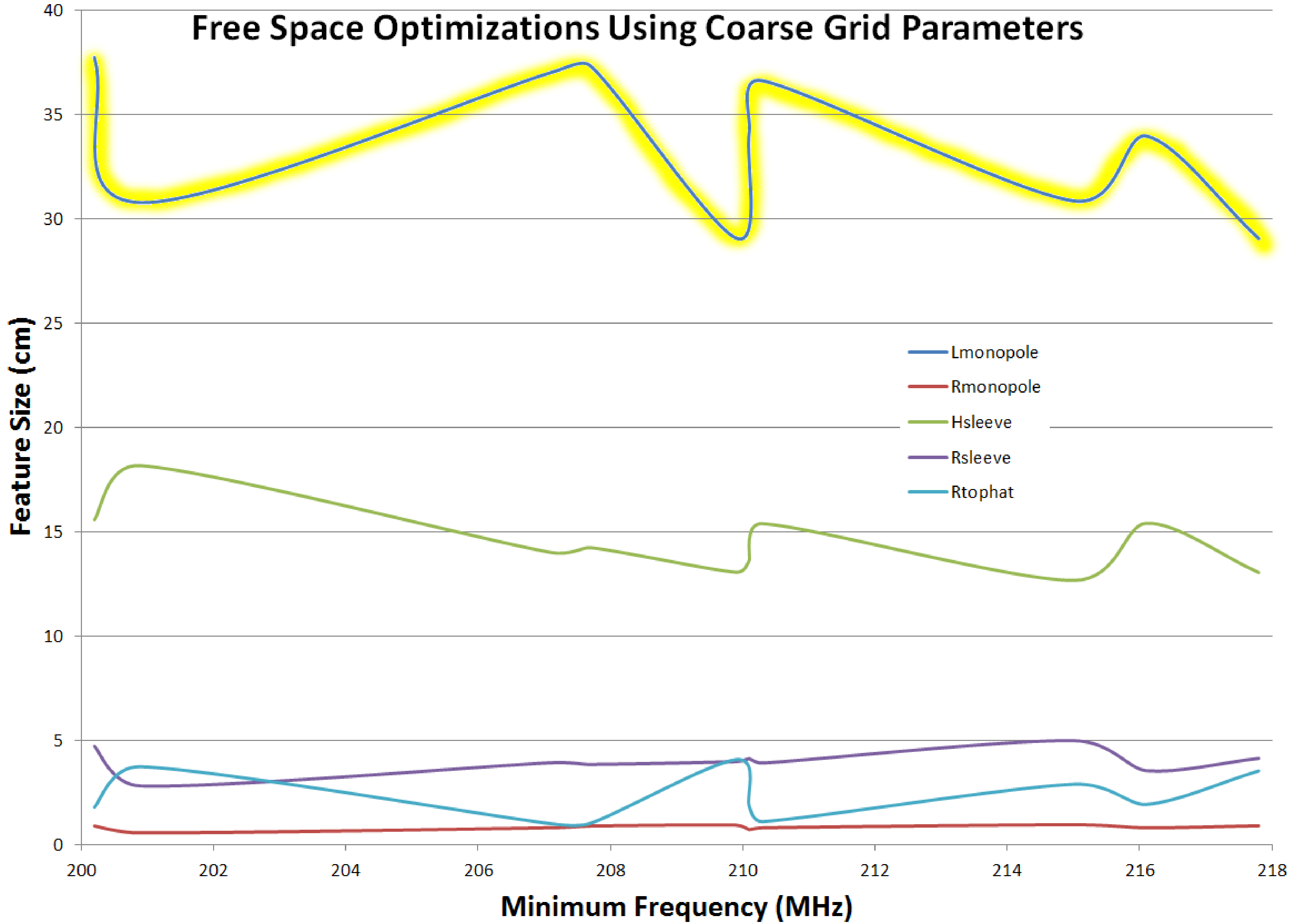
- Try the optimizations again
  - Run 10 more optimizations
  - Look for trends in the parameter values
- Focus on the free space scenario, because it seems to be the least restrictive
- Since we are only looking for trends, we can use a coarser grid to speed up the process
  - Average time per generation: 2.7 - 3.9 minutes
  - Number of generations: 2 - 11
  - All ten optimizations completed in 3.25 hours

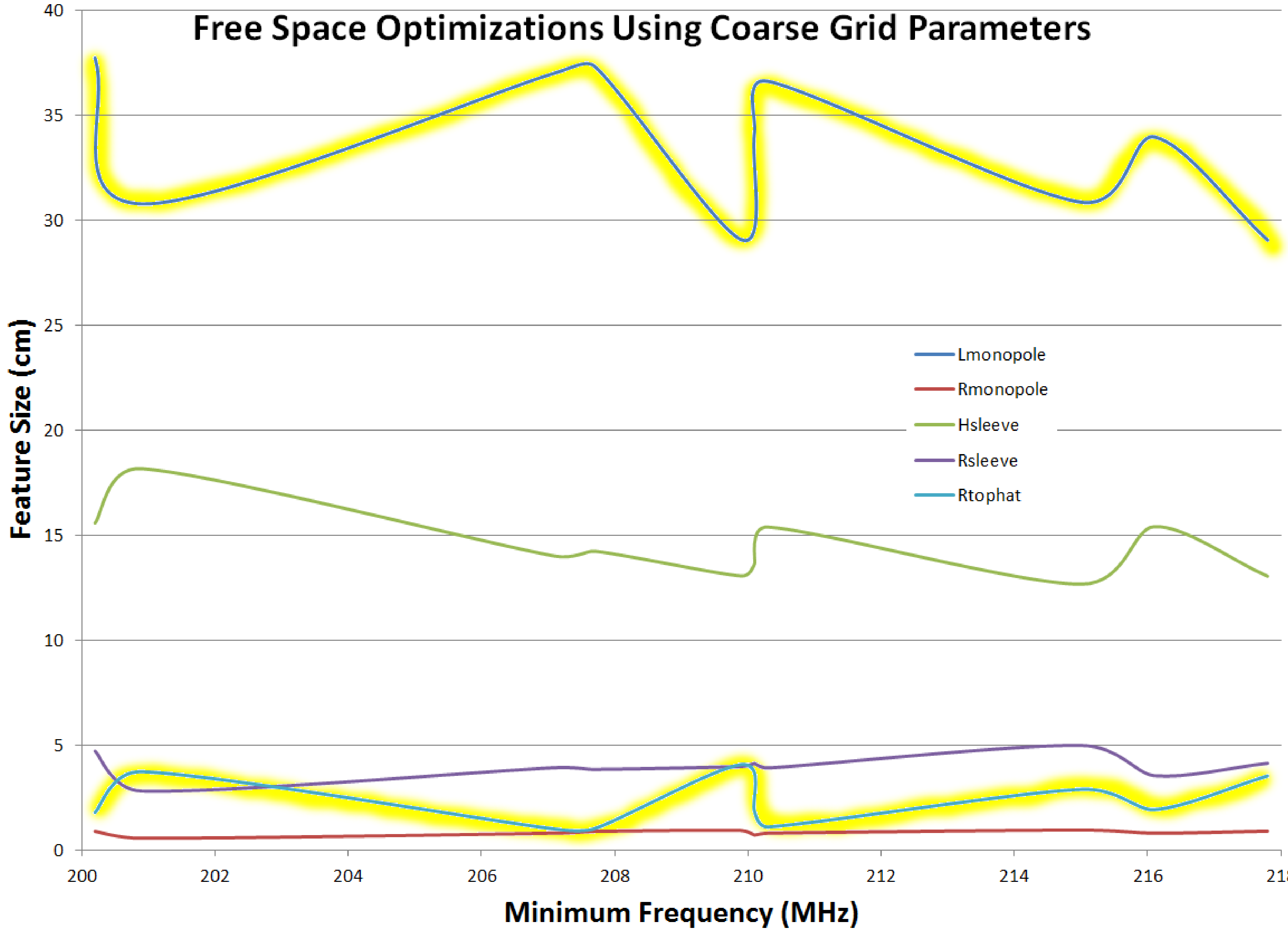
Observation of Results

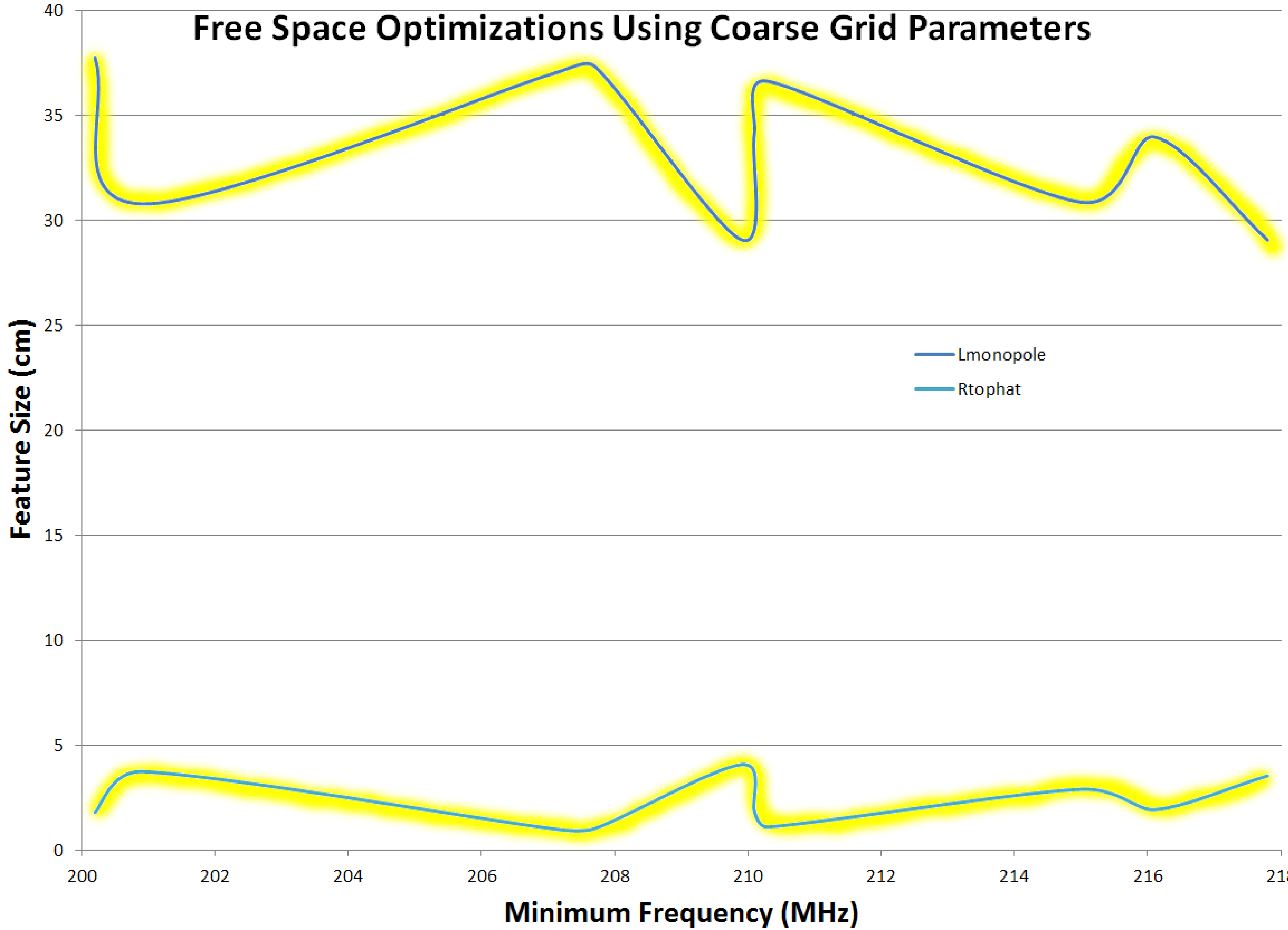
- A sufficient response at the low frequency range in the wet ground scenario was not possible.
- Generate a plot of parameter values versus minimum achieved frequency to look for trends.
- In the following plots, a relationship emerges between the monopole length and the top hat radius.



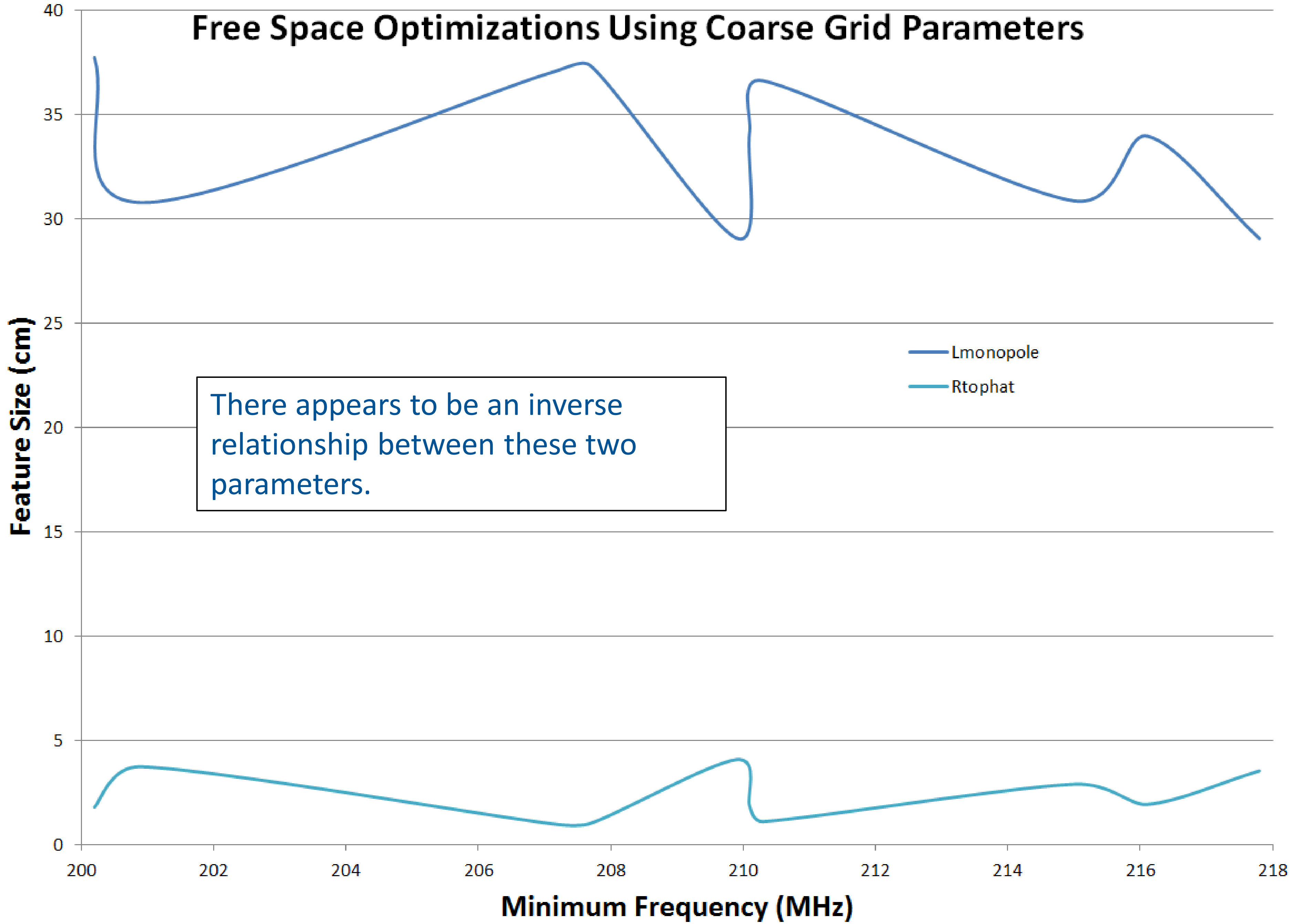
Free Space Optimizations Using Coarse Grid Parameters
Feature Size (cm)
Minimum Frequency (MHz)
0
5
10
15
20
25
30
35
40
200
202
204
206
208
210
212
214
216
218
Lmonopole
Rmonopole
Hsleeve
Rsleeve
Rtophat


Free Space Optimizations Using Coarse Grid Parameters
Feature Size (cm)
Minimum Frequency (MHz)
Lmonopole
Rmonopole
Hsleeve
Rsleeve
Rtophat
0
5
10
15
20
25
30
35
40
200
202
204
206
208
210
212
214
216
218

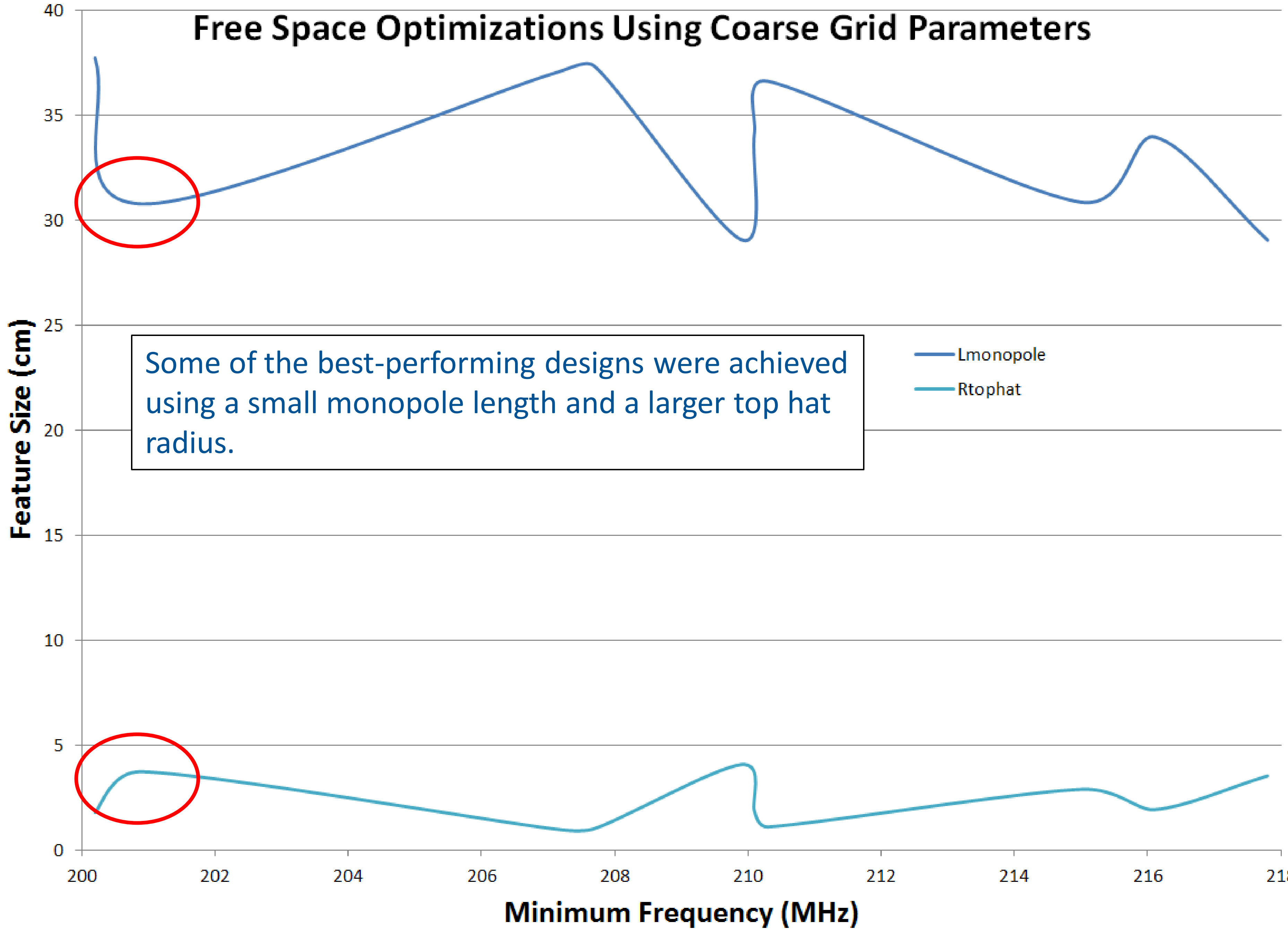

Free Space Optimizations Using Coarse Grid Parameters
Feature Size (cm)
Minimum Frequency (MHz)
0
5
10
15
20
25
30
35
40
200
202
204
206
208
210
212
214
216
218
Lmonopole
Rmonopole
Hsleeve
Rsleeve
Rtophat

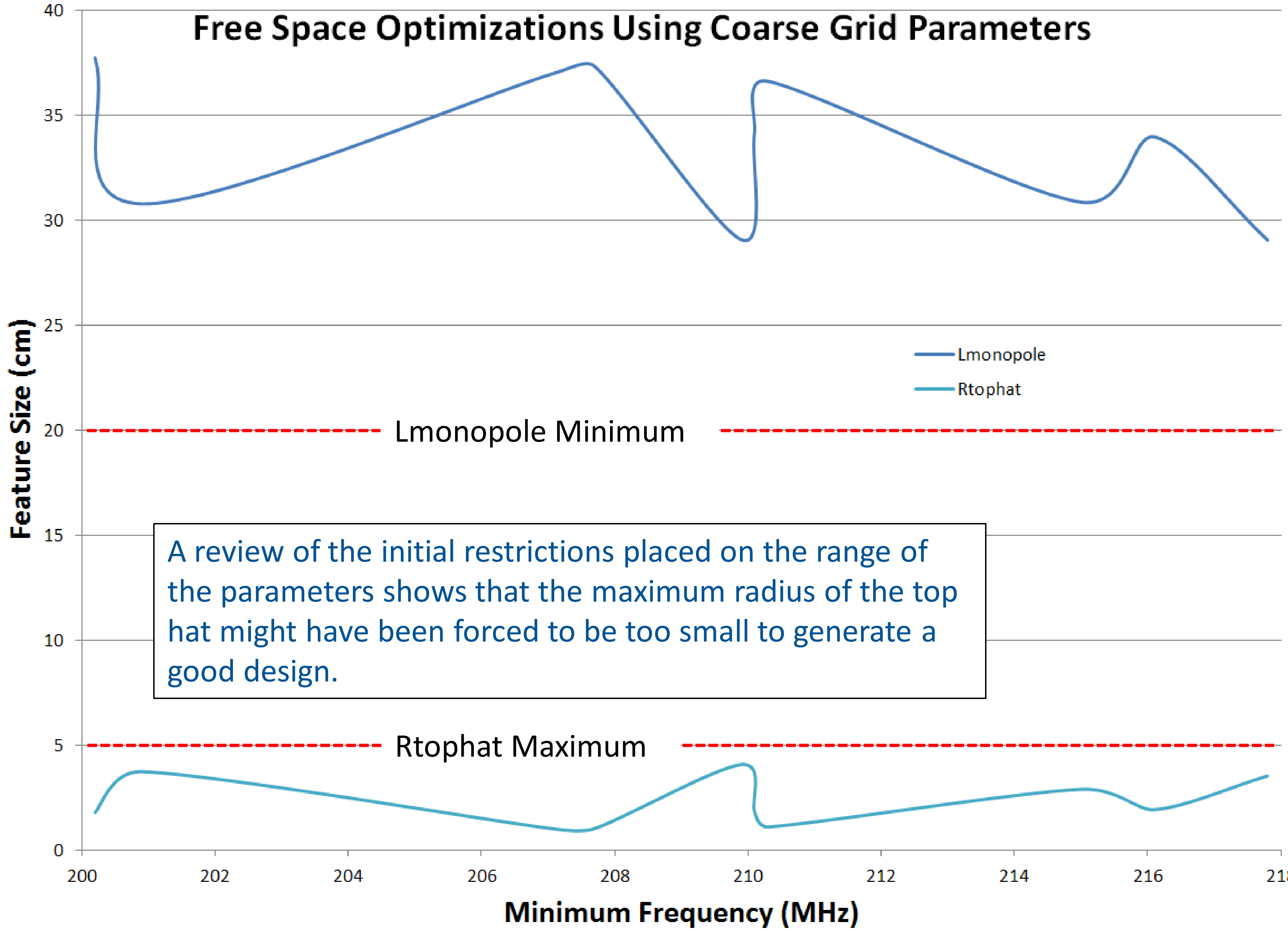


Free Space Optimizations Using Coarse Grid Parameters
Feature Size (cm)
Minimum Frequency (MHz)
Lmonopole
Rtophat
0
5
10
15
20
25
30
35
40
200
202
204
206
208
210
212
214
216
218



Free Space Optimizations Using Coarse Grid Parameters
Feature Size (cm)
Minimum Frequency (MHz)
0
5
10
15
20
25
30
35
40
200
202
204
206
208
210
212
214
216
218
Lmonopole
Rtophat
There appears to be an inverse relationship between these two parameters.

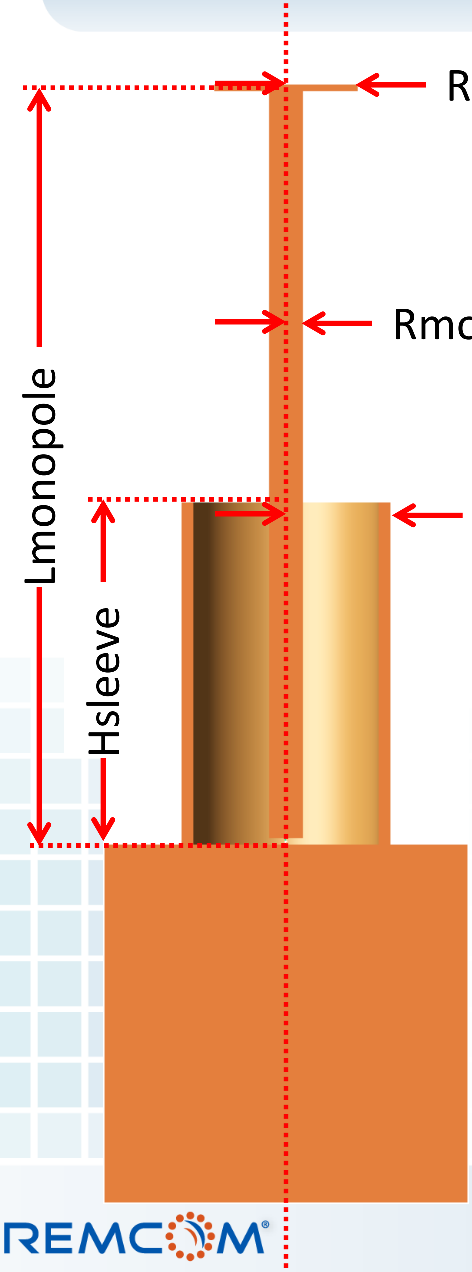

Free Space Optimizations Using Coarse Grid Parameters
Some of the best-performing designs were achieved using a small monopole length and a larger top hat radius.
Lmonopole
Rtophat
Feature Size (cm)
Minimum Frequency (MHz)
0
5
10
15
20
25
30
35
40
200
202
204
206
208
210
212
214
216
218


Free Space Optimizations Using Coarse Grid Parameters
Feature Size (cm)
40
35
30
25
20
15
10
5
0
Lmonopole
Rtophat
Lmonopole Minimum
A review of the initial restrictions placed on the range of the parameters shows that the maximum radius of the top hat might have been forced to be too small to generate a good design.
Rtophat Maximum
200
202
204
206
208
210
212
214
216
218
Minimum Frequency (MHz)

Revised Optimization

- Given this new information, return to the PSO optimization over wet ground and revise the parameter limits.
- Allow for shorter monopole designs by reducing the minimum bound for Lmonopole.
- Allow for larger top hat radii by adjusting the upper bound.
- Adjust the sleeve height to prevent the antenna from shorting out.

PSO Setup



Parameter	Min (cm)	Max (cm)
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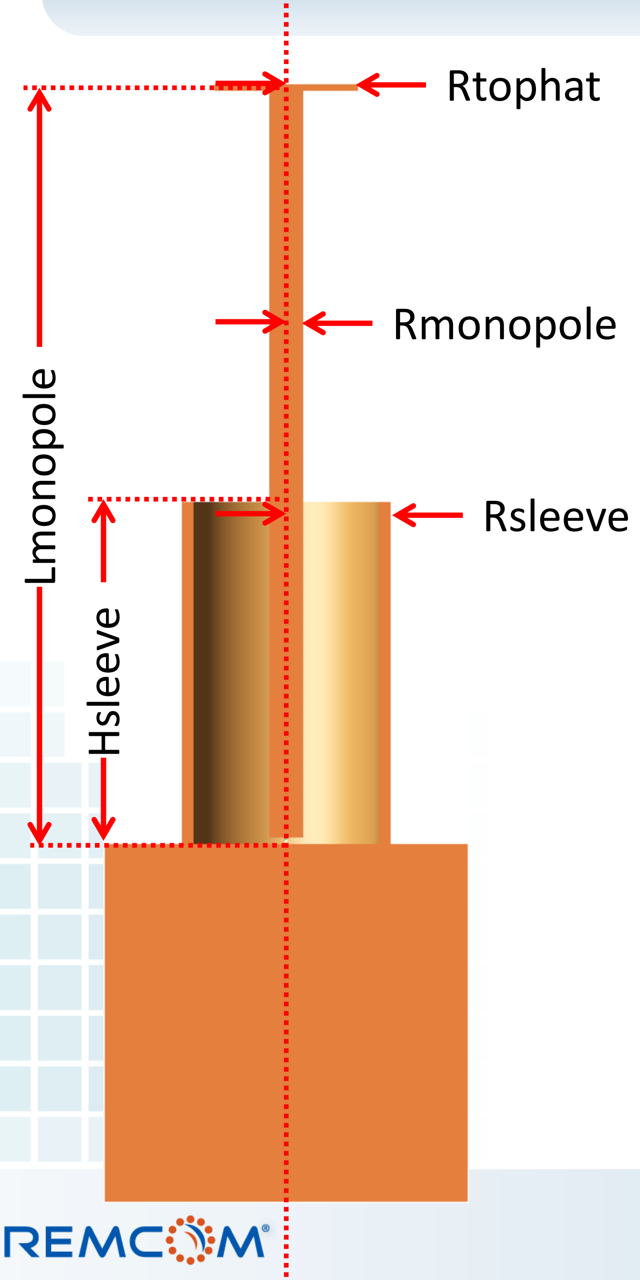
Hsleeve	5.0	19.0
Rsleeve	2.0	7.0
Rtophat	1.0	5.0

Original constraints were too restrictive.

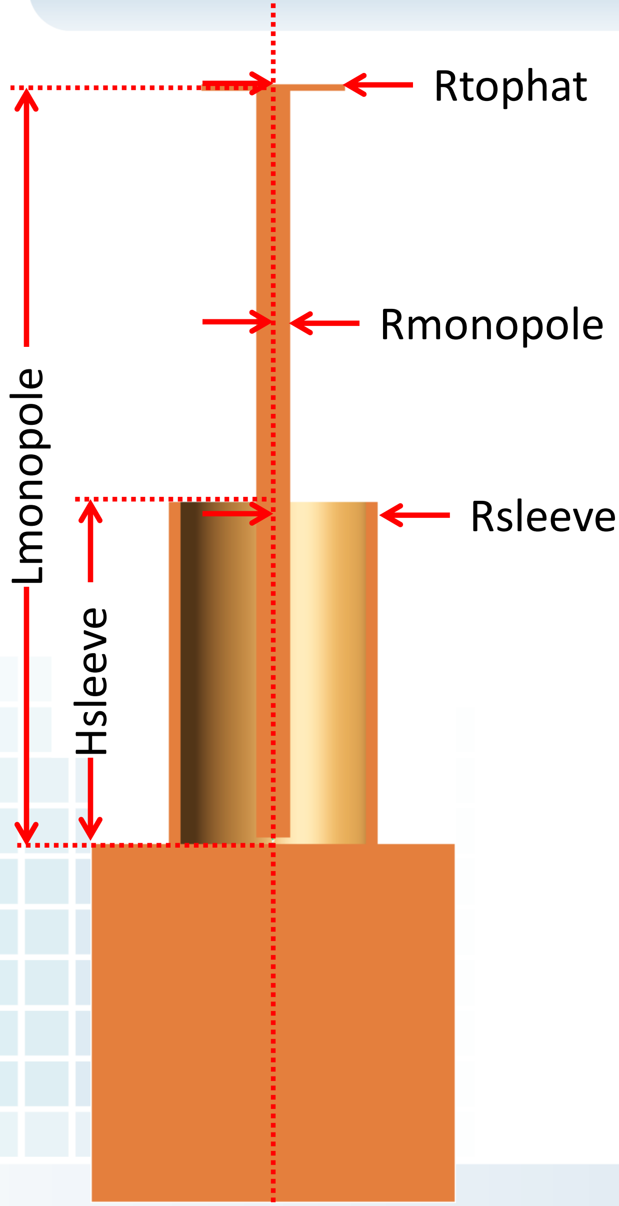
PSO Setup



Parameter	Min (cm)	Max (cm)
Lmonopole	5.0	40.0
Rmonopole	0.2	2.0
Hsleeve	2.0	19.0
Rsleeve	2.0	7.0
Rtophat	1.0	8.0

Revised constraints allow for smaller monopoles with larger top hat radii.

PSO Setup



Parameter	Min (cm)	Max (cm)
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Hsleeve	2.0	19.0
Rsleeve	2.0	7.0
Rtophat	1.0	8.0

- Re-run with new bounds
- Five Optimizations
  - 18 Particles
  - 600 Generations

PSO Performance

- Average time per generation: 12.4 - 22.9 minutes
- Number of generations: 16 - 211
- Optimization times: 3.3 - 80.4 hours
- All five optimizations completed in under five days

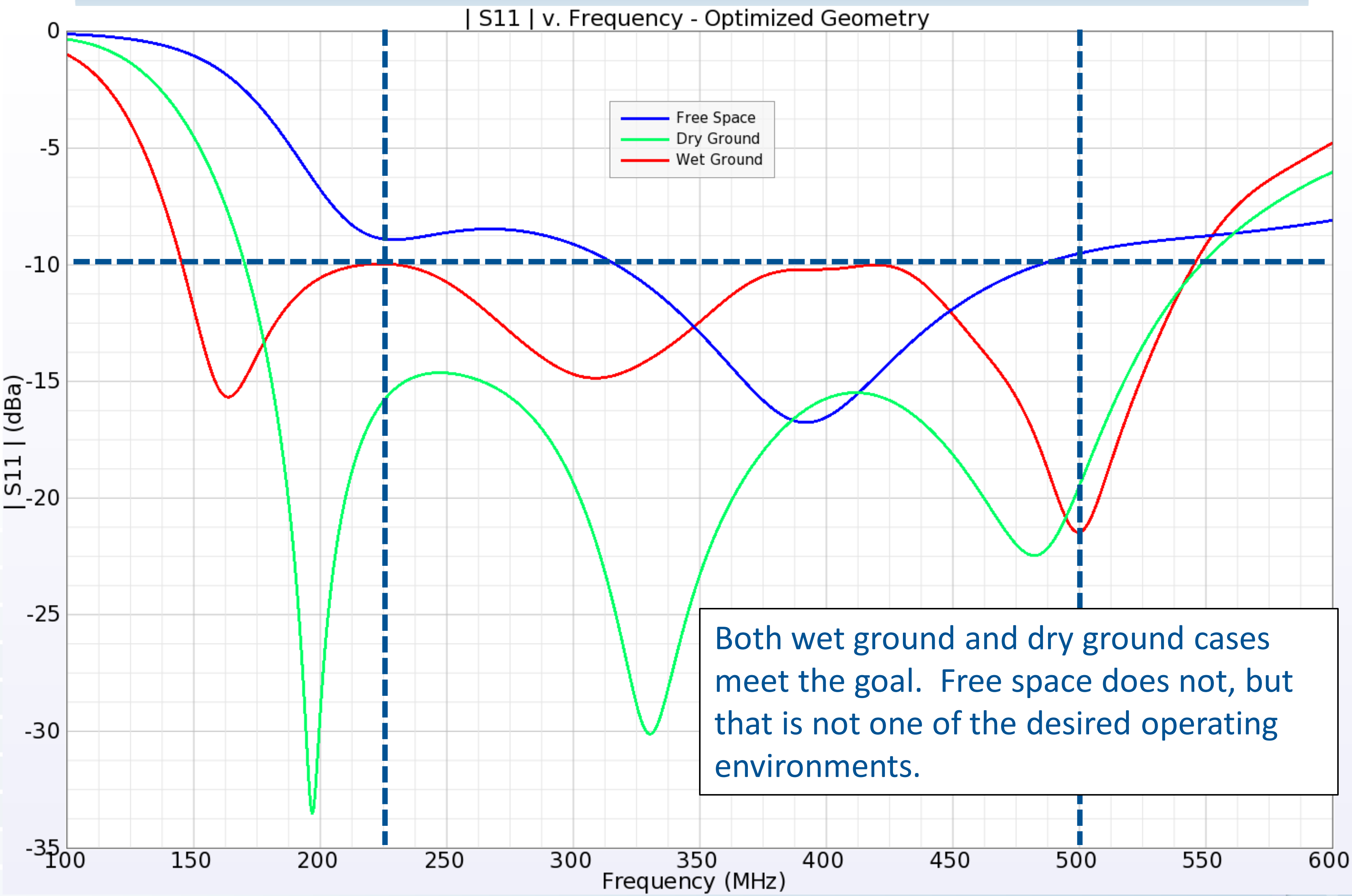
Optimization Results

- A variety of acceptable designs were found.
- The second optimization may be best suited to the needs of this project.

Lmonopole (cm)	Rmonopole (cm)	Hsleeve (cm)	Rsleeve (cm)	Rtophat (cm)	Min Frequency (MHz)	Max Frequency (MHz)
9.61	1.12	2.47	3.13	7.92	223.4	504.1
20.32	0.5	16.06	2.33	7.96	145.2	545.7
9.65	1.13	2.02	2.9	7.94	220.5	504.7
9.63	1.11	2	2.97	7.87	222.2	503.3
10.48	1.27	2.02	4.01	7.98	212.2	502.9

Compare Result to Design Goals

- Broadband operation:
  - 225 MHz - 500 MHz
  - Return loss <= -10 dB
- Uniform pattern in the horizontal plane (< 3dBi variation)
- High gain (>= 5 dBi)
- Near constant gain over bandwidth
- Preference for low-profile solution
- Function over a variety of ground conditions


| S11 | v. Frequency - Optimized Geometry
Free Space
Dry Ground
Wet Ground
| S11 | (dBa)
0
-5
-10
-15
-20
-25
-30
-35
100
150
200
250
300
350
400
450
500
550
600
Frequency (MHz)
Both wet ground and dry ground cases meet the goal. Free space does not, but that is not one of the desired operating environments.

Compare Result to Design Goals

- ✓ Broadband operation:
  - 225 MHz - 500 MHz
  - Return loss <= -10 dB
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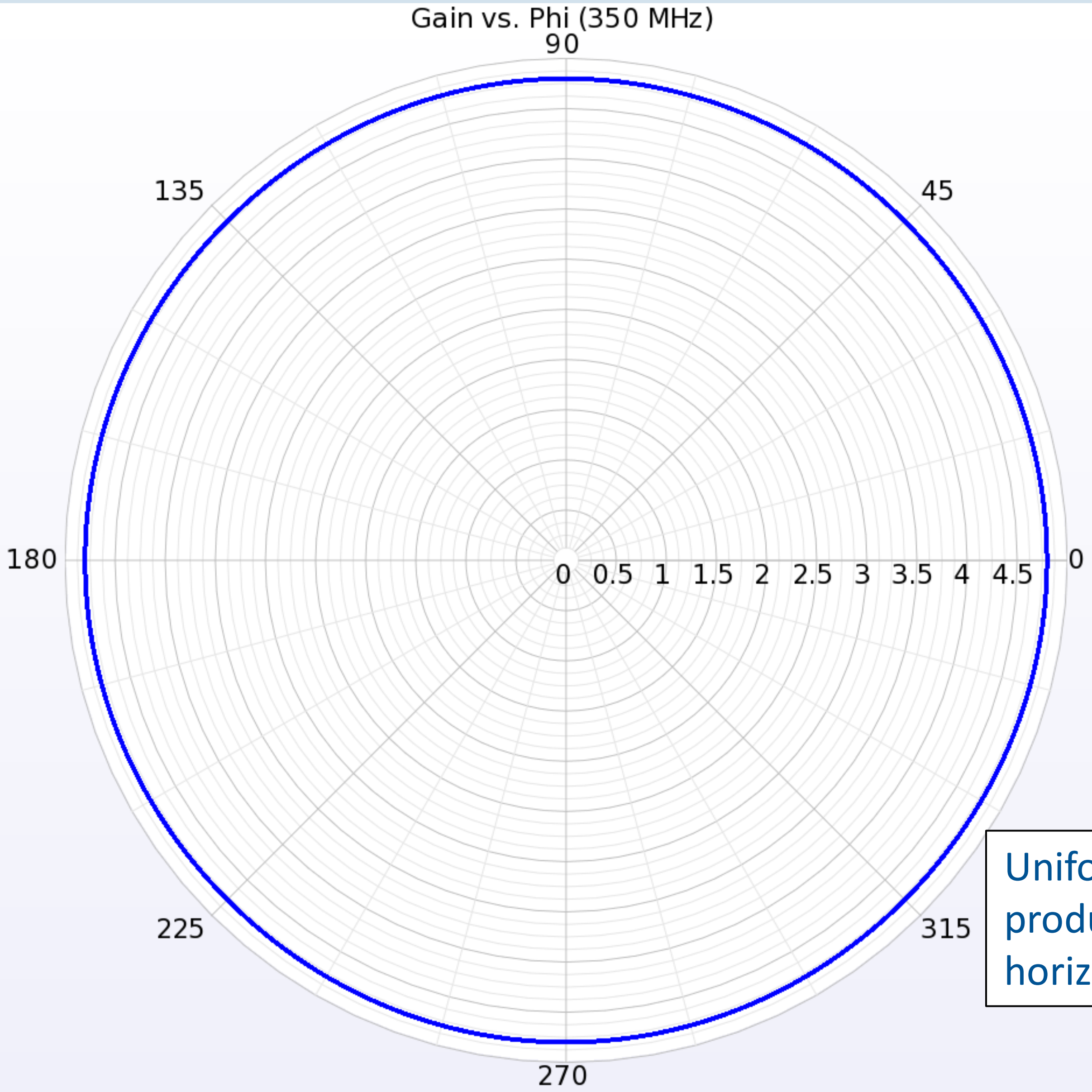

Uniform gain produced in horizontal plane

Compare Result to Design Goals

- ✓ Broadband operation:
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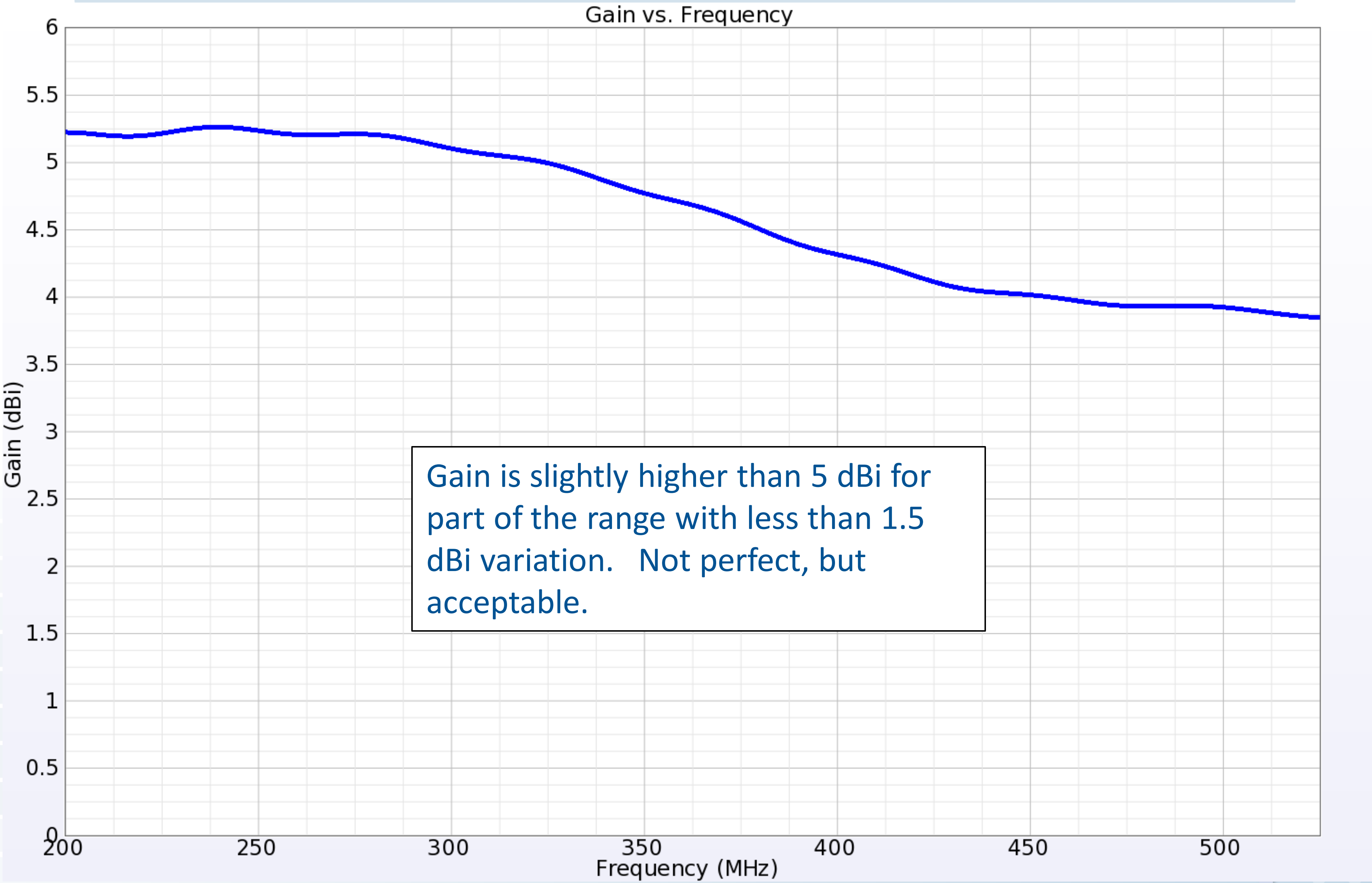
Gain vs. Frequency
Gain (dBi)
Frequency (MHz)
6
5.5
5
4.5
4
3.5
3
2.5
2
1.5
1
0.5
0
200
250
300
350
400
450
500
Gain is slightly higher than 5 dBi for part of the range with less than 1.5 dBi variation. Not perfect, but acceptable.

Compare Result to Design Goals

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Compare Result to Design Goals

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- ✓ Function over a variety of ground conditions

Conclusions

- When designing an antenna, incorporate as much of the operating environment as possible.
  - This may limit your choice of simulation tools.
  - The FDTD method is a robust technique capable of simulating any environment.
- The random nature of stochastic global optimization techniques can be used to gain insight into complex structures with interdependent parameters.
  - Use the least restrictive design environment to generate a variety of solutions.
  - Employ a coarse grid to speed optimization when looking for trends.

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