VHF/UHF Propagation Planning for Amateur Radio Repeaters

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Speaker's Biography

- **Stephen D. Stearns**
- **Technical Fellow, ret., Northrop Grumman Corp.**
- **40 years experience in electronic systems**
  - Northrop Grumman, TRW, GTE Sylvania, Hughes Aircraft
  - Electromagnetic and signal processing systems for communications and radar surveillance, cochannel signal separation, measurement, identification, characterization, polarimetric array signal processing of ionospheric skywave signals for precision geolocating HF emitters
  - Recent work: Vector-sensor antennas; Non-Foster circuits; antennas for radiating localized, non-diffracting, OAM Bessel-Vortex beams
- **FCC licenses**
  - Amateur Radio Extra Class
  - 1st-Class Radiotelephone
  - General Radio Operator License (GROL)
  - Ship Radar Endorsement
- **Education**
  - Stanford – under Prof. T.M. Cover
  - USC – under Profs. H.H. Kuehl and C.L. Weber
  - CSUF – under Profs. J.E. Kemmerly and G.I. Cohn
- **More than 100 publications and presentations, both professional (IEEE) and hobbyist (Amateur Radio)**

Abstract

Terrestrial radio, TV, cellular, and wireless systems are not “line-of-sight” despite what you’ve heard. Otherwise, your HT and smart phone would not work indoors, and your WiFi router signal would not reach other rooms.

Today, powerful computer programs are used universally to design such systems. The hard part of the calculation is to determine RF path loss while properly accounting for reflection, refraction, diffraction, and shadowing effects.

One algorithm, the Longley-Rice algorithm, was developed to specifically model radio propagation over irregular terrain. This algorithm became the basis for the government’s Irregular Terrain Model (ITM) software, which, in turn, was adopted by the FCC as the approved method for computing service contours and interference between fixed stations.

We review propagation theory, prediction algorithms, and show how to compute the two-way service contours of repeaters for high-reliability communication and for mountain top DX fun.

Topics

- **Introduction**
- **Propagation mechanisms at VHF/UHF**
  - Reflection, refraction, diffraction, shadowing, scattering
- **Algorithms and techniques for link, system, and cell planning**
- **Free software for Radio Amateurs**
  - Link analysis versus coverage analysis (service contours and cell boundaries)
- **Example: SPECS repeaters**
  - Coverage analysis for 2-meter, 1.25-meter, and 70-cm machines
  - High reliability “assured” coverage for primary mission
  - Lower reliability coverage for long-range DX fun

Introduction

Questions

- Does light travel on straight lines?
- Do radio waves travel on straight lines?
- Do VHF and UHF radio waves travel on straight lines?
- Do VHF and UHF communications need Line-of-Sight (LOS) paths?

FEKO Featured in QST, October 2016

Near Fields of a Mobile Mounted 2 Meter Antenna

The author uses *FEKO*, a patch-based computational software package, to reveal EM fields around a vehicle.

Keith Snyder, KI6BDR

FEKO is a computational electromagnetic (CEM) tool that I used to calculate the antenna pattern of a 2 meter antenna located on the center of the roof of a sedan-type automobile. *FEKO* computer code can calculate the electromagnetic fields both inside and outside the vehicle. I show images of the near fields around the vehicle.

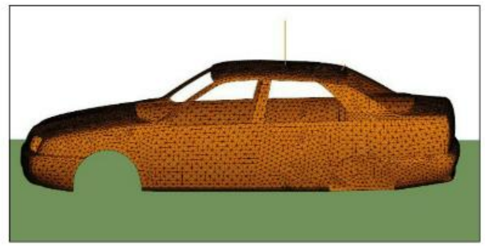


Figure 1 — Triangular patch model of a car includes a 19-inch wire antenna on the roof.

Many radio amateurs are familiar with modern NEC-based computer software like *EZNEC* and 4*nec*2 used to calculate the fields of wire antennas and wire structures in the presence of a ground.[1,2,3] These computer software codes facilitate antenna analysis as a function of frequency, antenna height above ground, along with antenna patterns in presence of wire models of structures. The *FEKO* computer code is similar in that, like the NEC codes, it uses the method of moments (MOM) and the Sommerfeld ground capabilities.

FEKO Software

FEKO uses triangular patches in the models so that we can represent arbitrary shapes such as the metal skin of an automobile or aircraft. *FEKO* stands for "feldberechnung für körper mit beliebiger oberfläche," which translates from German to "field calculations for arbitrarily shaped structures."[4]

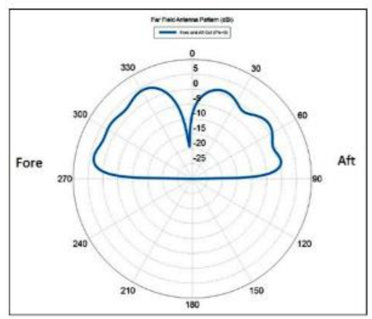


Figure 2 — Elevation pattern for a quarter-wave antenna on car at 147 MHz.

I first encountered *FEKO* at the Applied Computational Electromagnetics Society meeting in Monterey, California in 2003. I met Dr C. J. Reddy, who helped me model a rolled-edge discone antenna. Later, I met Dr. Ulrich Jakobus, who wrote the code as part of his research activities at the University of Stuttgart in 1991. Capabilities of *FEKO* software include Finite Element Method (FEM), Method of Moments (MOM), Multi-Level Fast Multipole Method (MLFMM), Physical Optics/Geometrical Optics (PO/GO), and UTD (Uniform Theory of Diffraction).[5]

Steve Stearns, K6OIK, in a presentation to the Foothill Amateur Radio Society, has compared several CEM tools including a few of the NEC software packages, along with *FEKO*.[6]

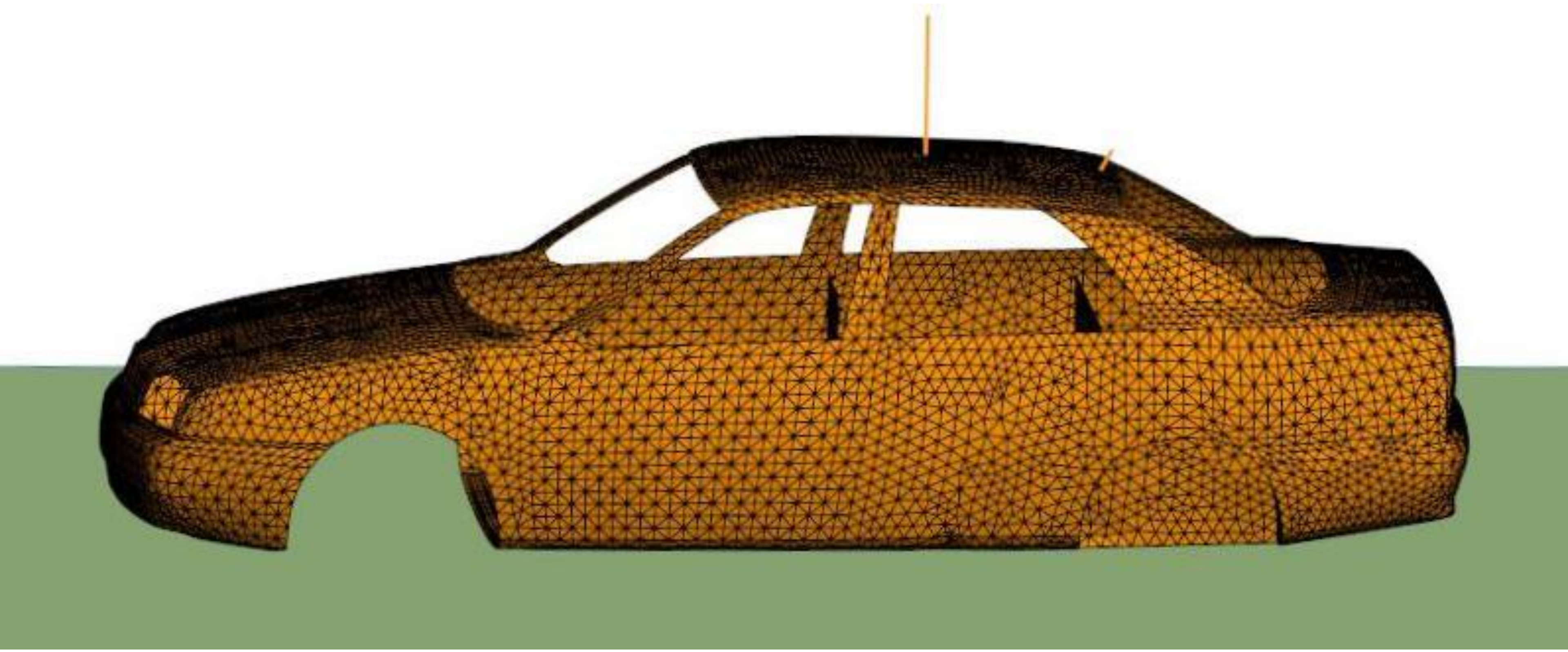
The Vehicle Model

I found a generic car model on the *FEKO* software web page that is already meshed with simple triangle patches. I modeled a quarter-wave monopole antenna on the roof to see the near and far fields at 147 MHz. The 19-inch-tall monopole is located near the center of the roof. Figure 1 shows the patch model of a car with the monopole on the roof.

The car model is composed of 21,602 triangles. There are also 31 wire segments used to model the 2 meter monopole and a short antenna on the back of the roof that is treated as a scatterer. The ground constants are a relative permittivity of 10, and conductivity of 0.005 S/m. The green plane under the car in Figure 1 indicates in *FEKO* that the Sommerfeld ground has been implemented.

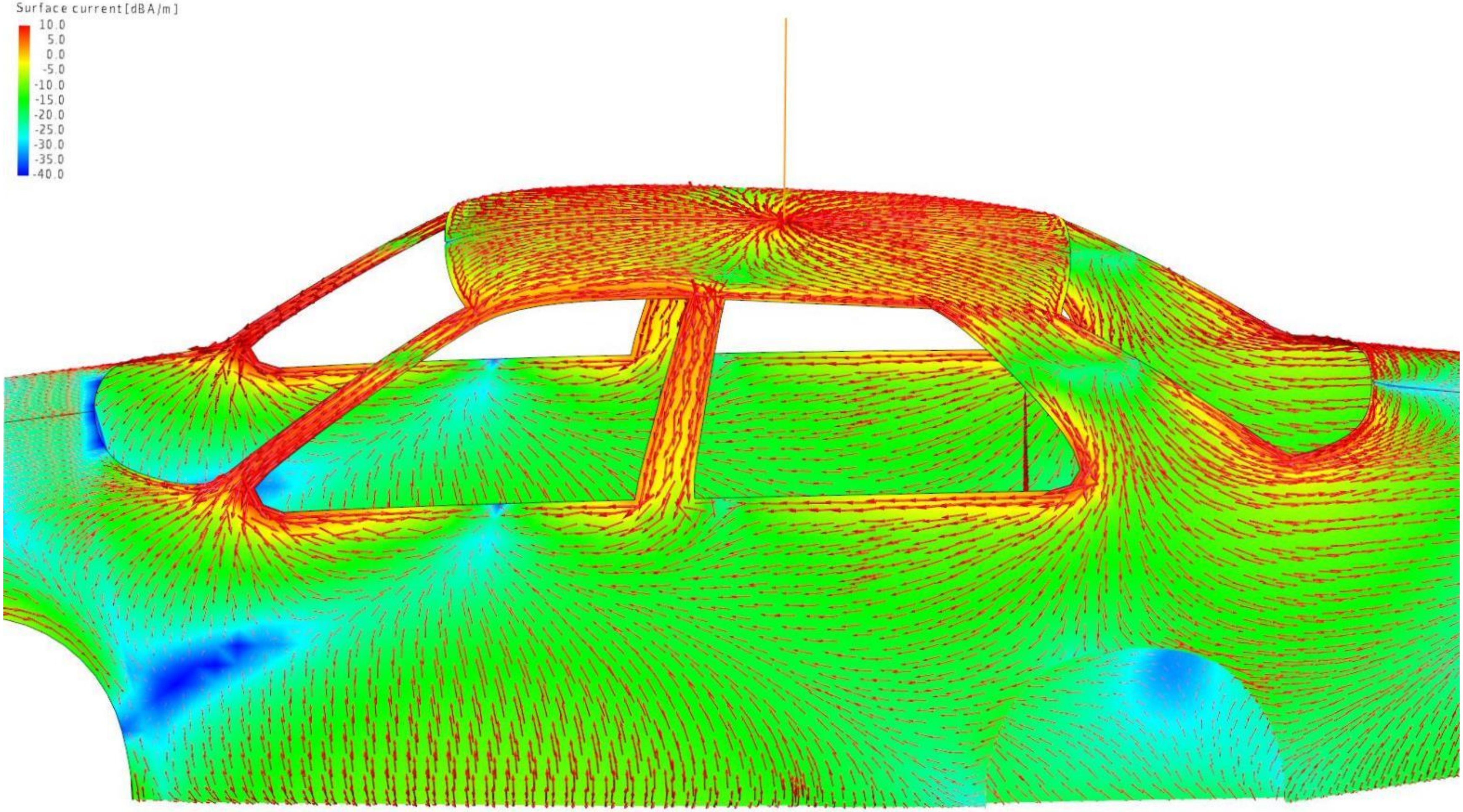
The output of the computer code indicates that the antenna is near resonance with an

Car with 2-Meter Monopole on Roof



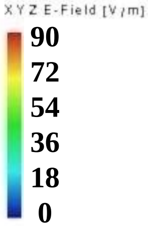
Courtesy of Keith Snyder, KI6BDR

Skin Currents

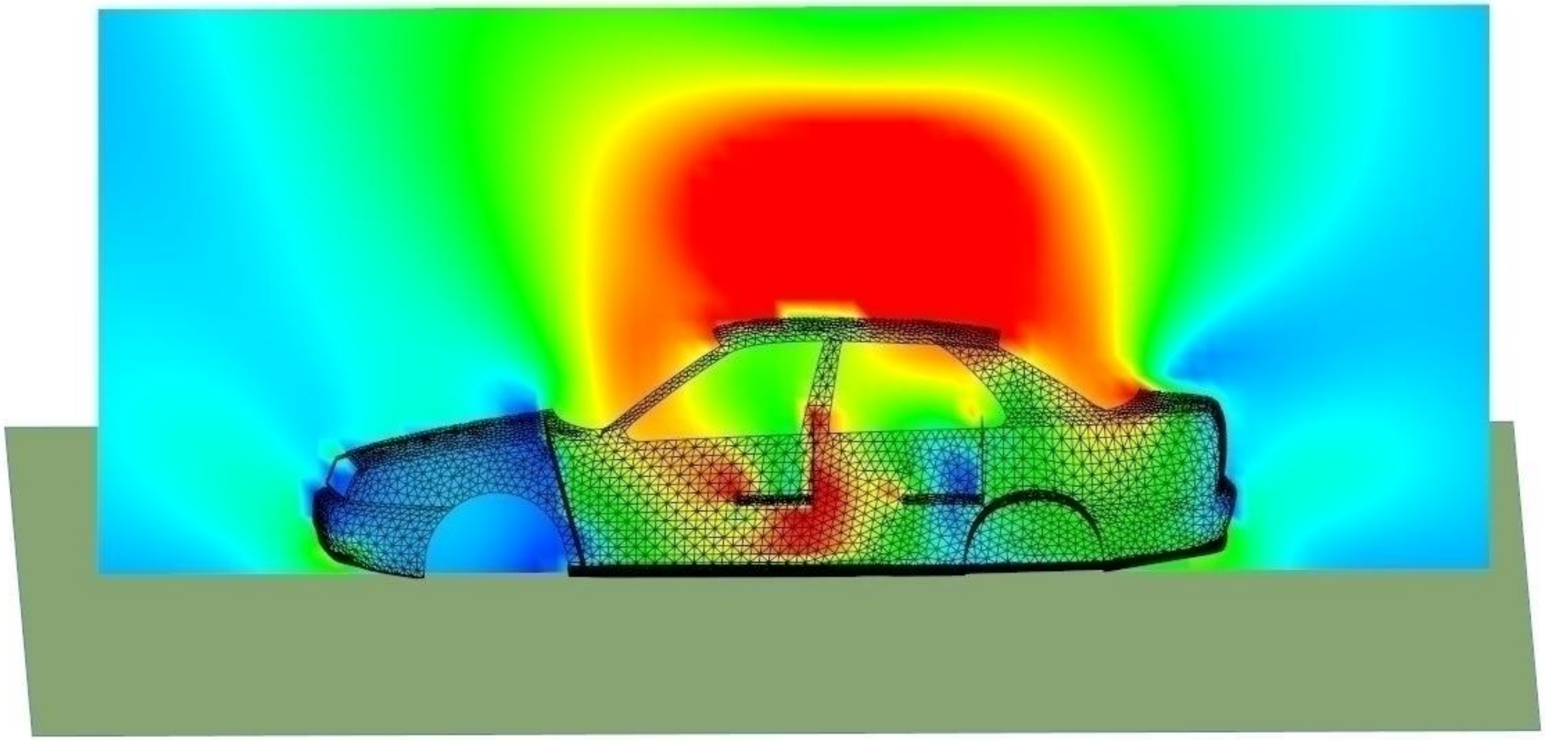


Courtesy of Keith Snyder, KI6BDR

Electric Field Strength in Longitudinal Plane

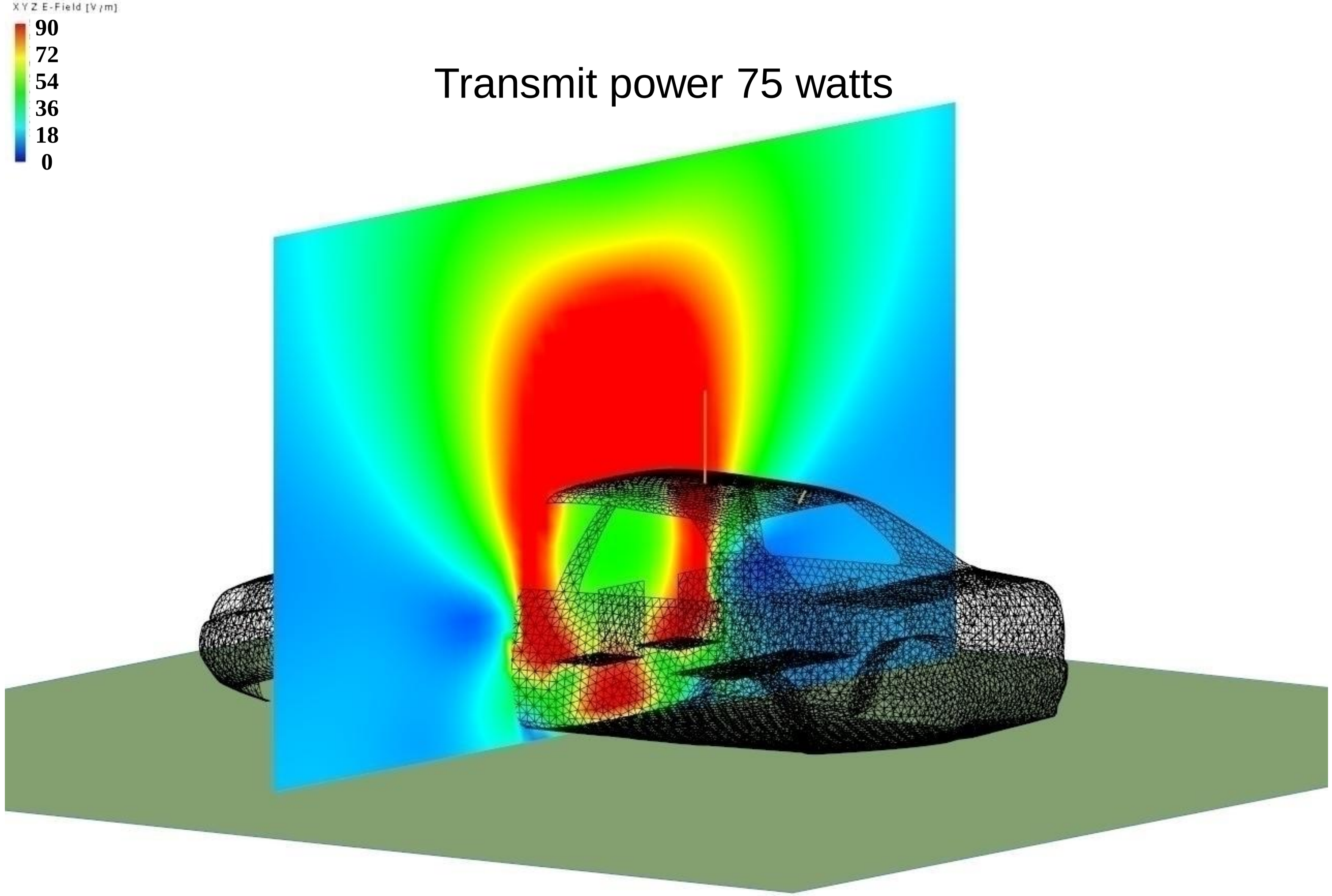


Transmit power 75 watts



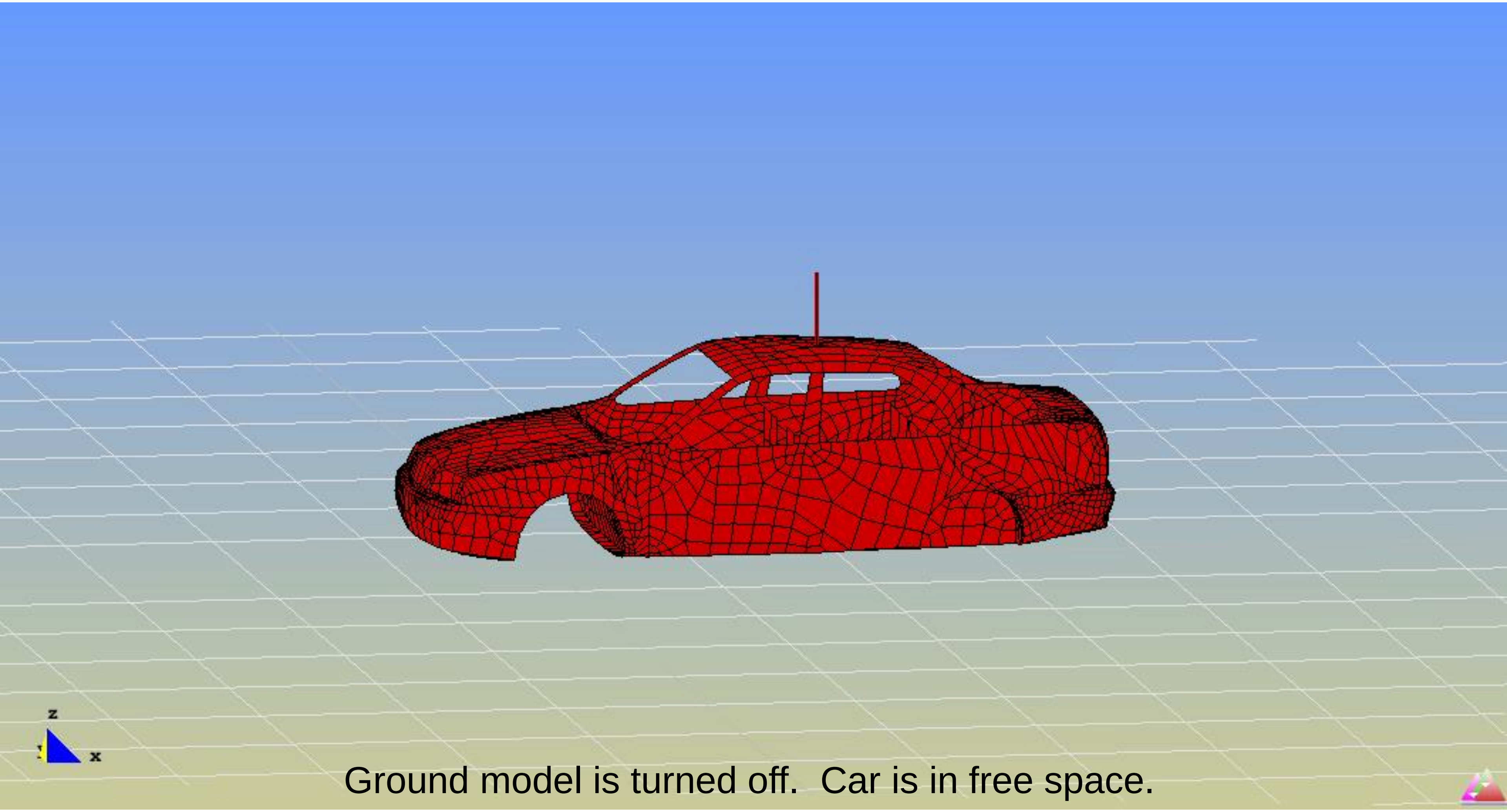
Courtesy of Keith Snyder, KI6BDR

Electric Field Strength in Transverse Plane



Courtesy of Keith Snyder, KI6BDR

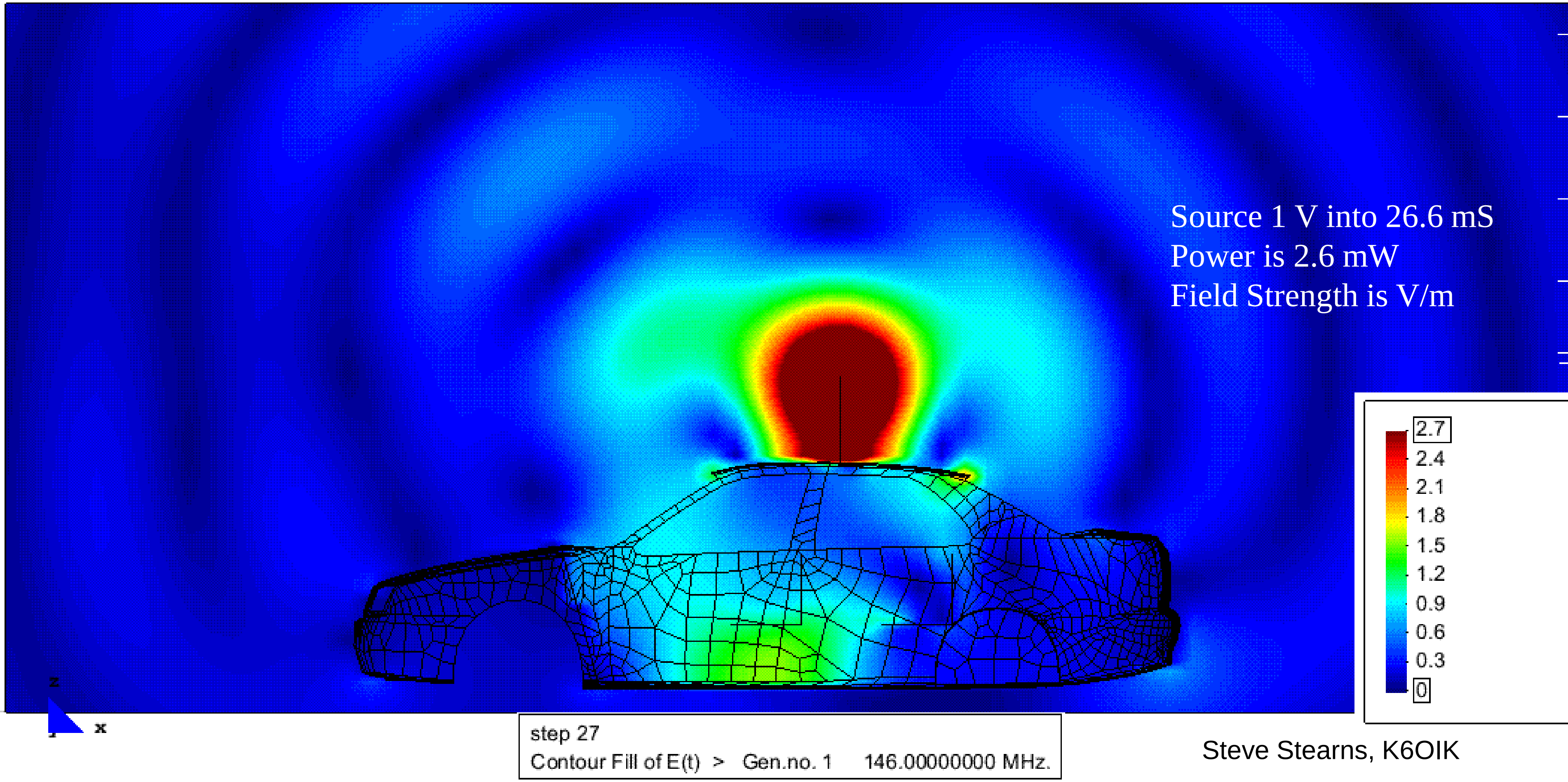
Quadrilateral Bilinear Surface Mesh



Ground model is turned off. Car is in free space.

Steve Stearns, K6OIK

|E| Field in Central Plane (y = 0)



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View PowerPoint in Slide Show mode (Shift F5) to see field animation.

The Lessons

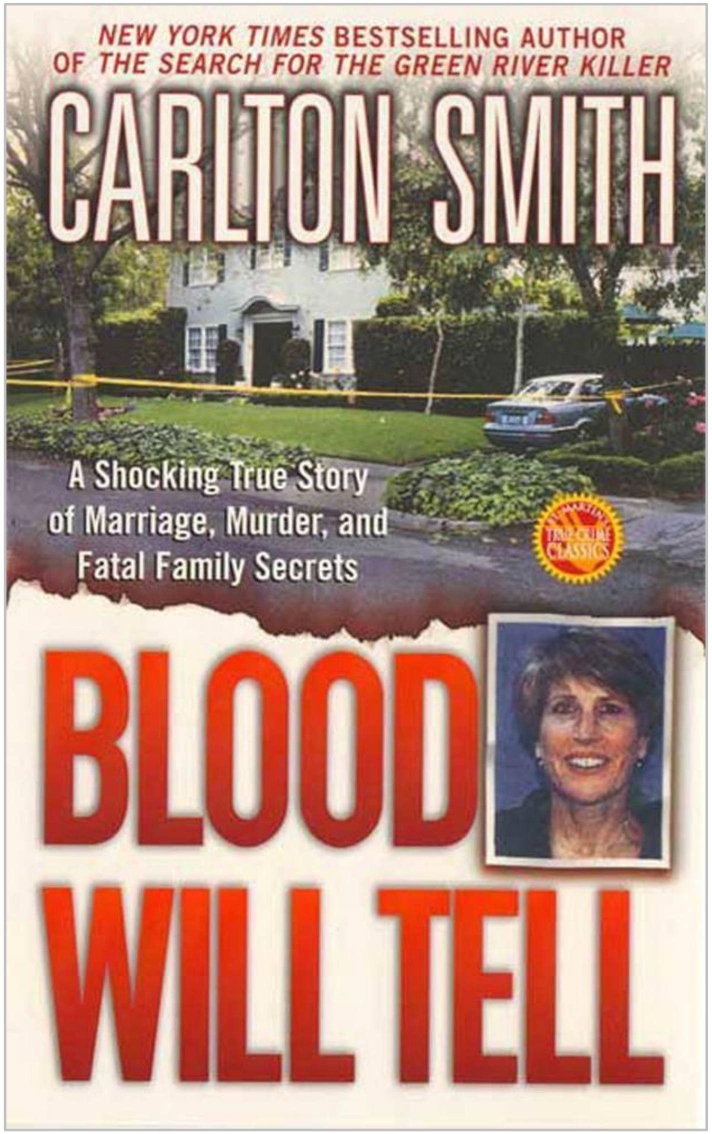
- RF propagation lesson

Electromagnetic waves do not always travel Line-of-Sight paths!

- RF safety lesson

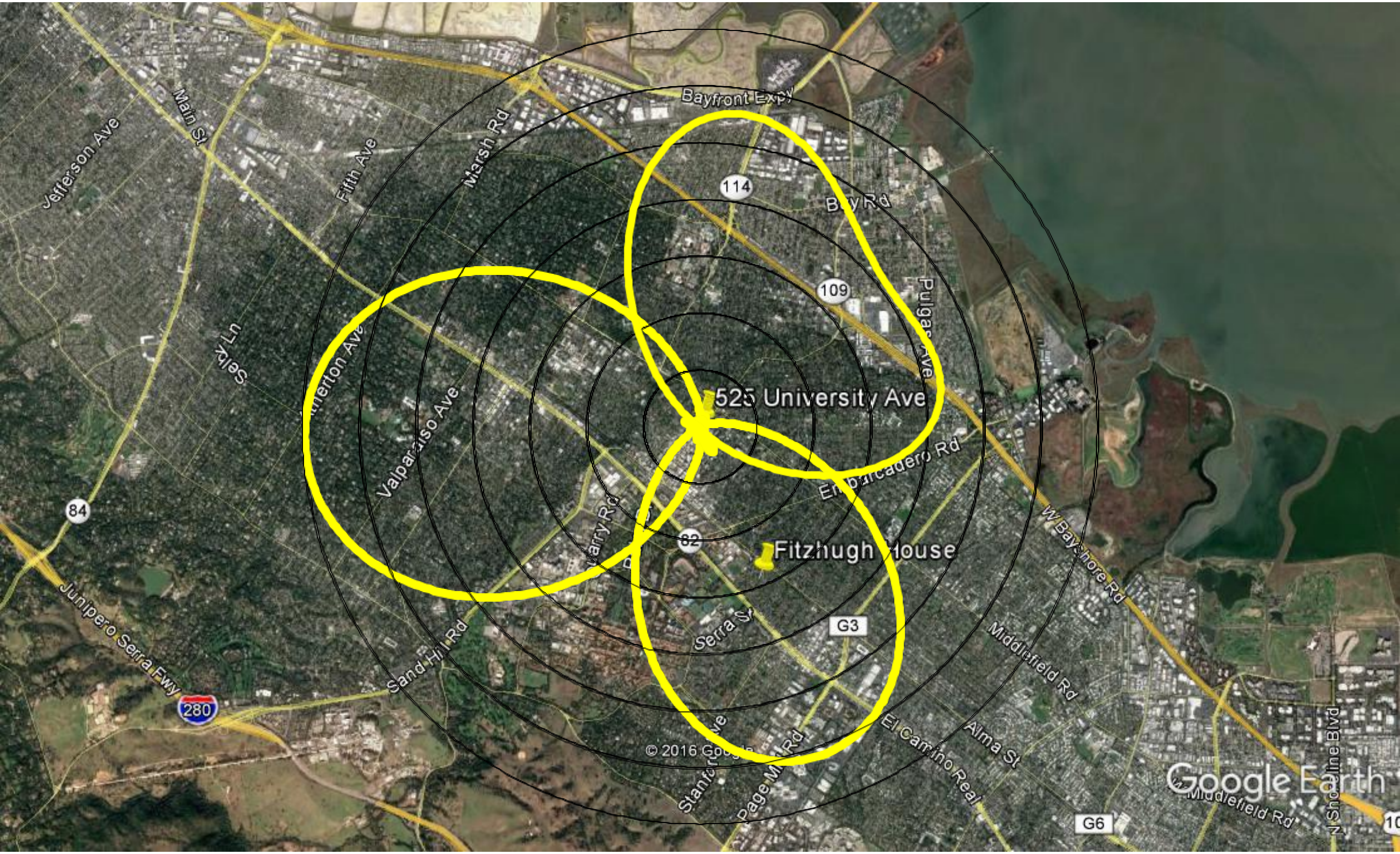
Mobile stations running 50 watts or more on 2 meters should do a station evaluation even though it's not required.

Palo Alto Murder – May 5, 2000



- **They Were The Perfect Family. . .**
  - For twenty years, Ken and Kristine Fitzhugh and their two sons had lived lives of comfortable middle-class normality in the university town of Palo Alto, California. Then came the shocking news that Kristine Fitzhugh was dead, the victim of a terrible accident... By the time the Palo Alto Police Department looked closer at the death of Kristine Fitzhugh, there could be only one conclusion. Someone had murdered Kristine in her own home, inflicting a series of horrific blows to the back of her head, and then cleaned up the mess to make it look like an accident. Who would do such a thing? Protesting his innocence, Kenneth Fitzhugh was arrested and tried for the murder of his wife. And as the case progressed, one by one, the hidden secrets of the Fitzhugh family came spilling out. . .
- ***Blood Will Tell* is the shocking true story of a seemingly happy family and the deadly secrets that led to murder.**

Verizon's Cellular Footprints of Site 167

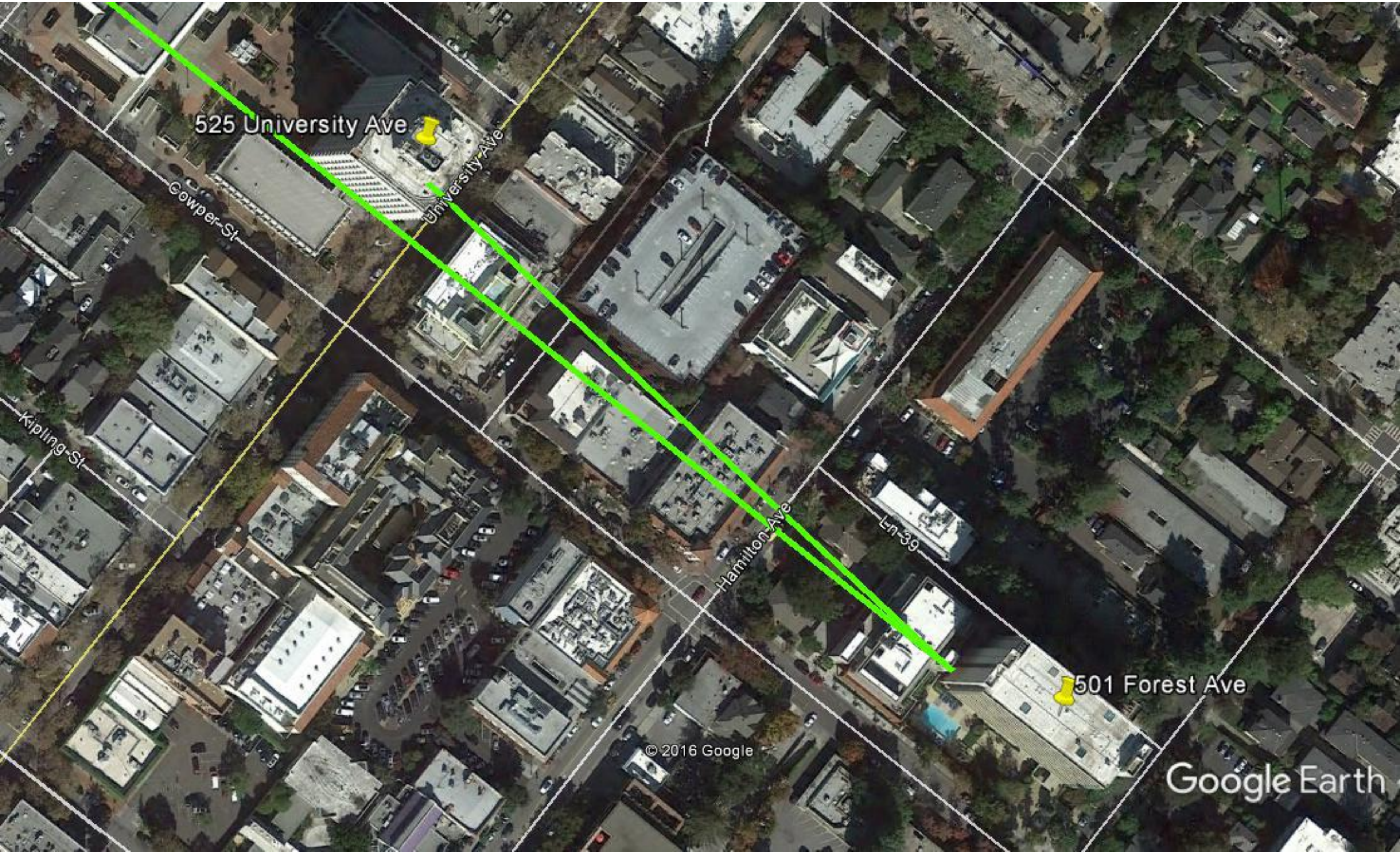


The Defense's Dilemma

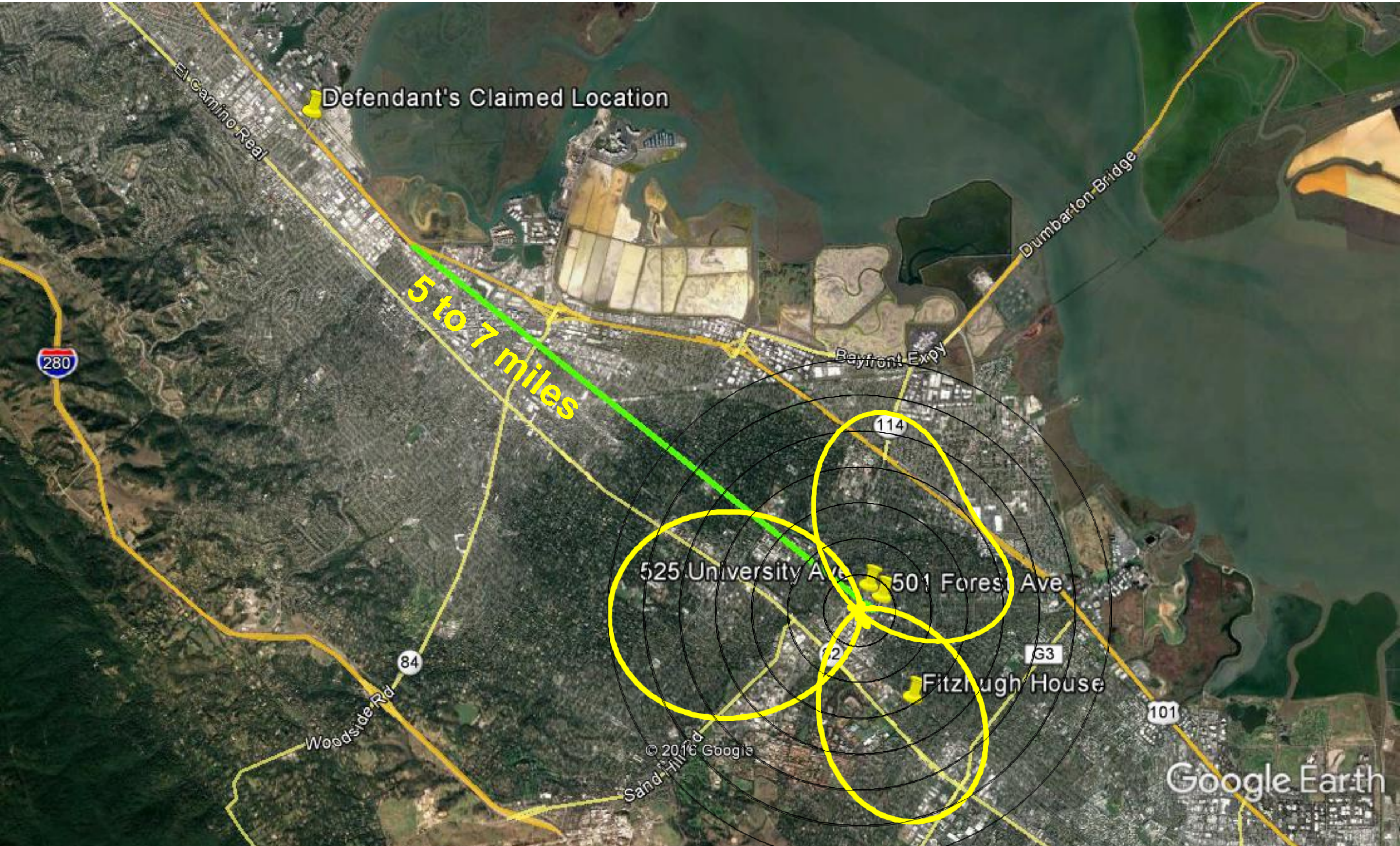
The View Looking Southeast from Site 167

The View Looking Northwest Toward Site 167

Where Would a Reflected Wave Go?



Answer – Along a Section of Highway 101



At Trial

- **Verizon Wireless cellular engineers testified for the prosecution that it was impossible for the south facing antenna to service the north side of Site 167**
- **They testified that a phone on the north side would connect to the Northeast or West facing antennas if a connection were to happen**
- **Expert Witness for the defense, an authority on RF systems and radio propagation, countered that a reflected path was plausible given analysis of**
  - Path geometry
  - Passive reflector's radar cross-section and scattering behavior
  - Orientations of antenna patterns of Site 167
  - Antenna patterns, signal strengths, and cell boundaries of other Verizon base stations on the peninsula
- **Expert Witness's drive tests of a phone in diagnostic mode further revealed phones did connect to the south facing antenna from locations north of Site 167**
- **Prosecutor became visibly angry as the phone evidence part of his theory of the murder collapsed**

The Rest of the Story

- **The story of the trial was documented in Carlton Smith's book *Blood Will Tell*, St. Martin's Press, 2003**
  - Award-winning journalist for *The Los Angeles Times* and *The Seattle Times* in the 1970s and 1980s
  - Finalist for the Pulitzer Prize in investigative reporting in 1988
- **Defendant Kenneth Fitzhugh was convicted of second-degree murder and sentenced to 15 years to life in prison**
- **The conviction was based on blood evidence, not cell phone evidence**
- **Kenneth Fitzhugh was paroled in 2012 for medical reasons**
- **He died eight months later at age 69**

The Moral

VHF and UHF radio signals do not always travel Line-of-Sight paths!

Propagation Mechanisms at VHF and UHF

- **Reflection**
  - Hard reflection off large objects – buildings, mountains
  - Multipath
- **Refraction**
  - Atmospheric bending due to temperature/pressure gradients
  - Analyzable for parabolic gradients
- **Diffraction**
  - Knife edge diffraction (Deygout, Causebrook, Giovaneli, Vogler)
  - Wedge diffraction
- **Shadowing**
  - Blockage behind large objects that isn't filled in by multipath or diffraction
- **Scattering**
  - General term for re-radiation from objects large and small
  - Depends on material properties and surface irregularity

You do not need a Line-of-Sight path to communicate on VHF or UHF!

Technician Exam Questions

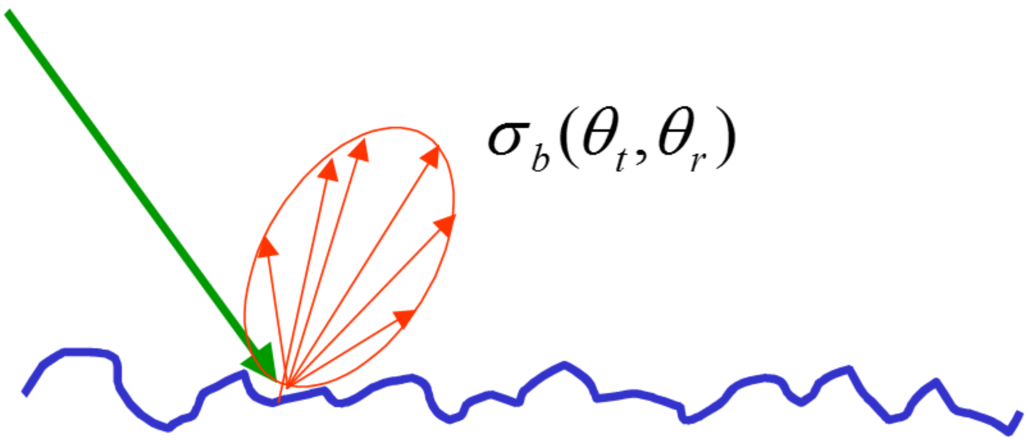
- **Refraction**
  - T3C02: Which of the following might be happening when VHF signals are being received from long distances?
    - A. Signals are being reflected from outer space
    - B. Signals are arriving by sub-surface ducting
    - C. Signals are being reflected by lightning storms in your area
    - **D. Signals are being refracted from a sporadic E layer**
- **Diffraction**
  - T3C05: Which of the following effects might cause radio signals to be heard despite obstructions between the transmitting and receiving stations?
    - **A. Knife-edge diffraction**
    - B. Faraday rotation
    - C. Quantum tunneling
    - D. Doppler shift
- **Scattering**
  - T3C06: What mode is responsible for allowing over-the-horizon VHF and UHF communications to ranges of approximately 300 miles on a regular basis?
    - **A. Tropospheric scatter**
    - B. D layer refraction
    - C. F2 layer refraction
    - D. Faraday rotation

Why Isn't the Moon's Reflection Round?

Cityscape's Reflection Isn't Just Upside Down

Reflection versus Scattering

- **Smooth surfaces reflect; irregular surfaces scatter**



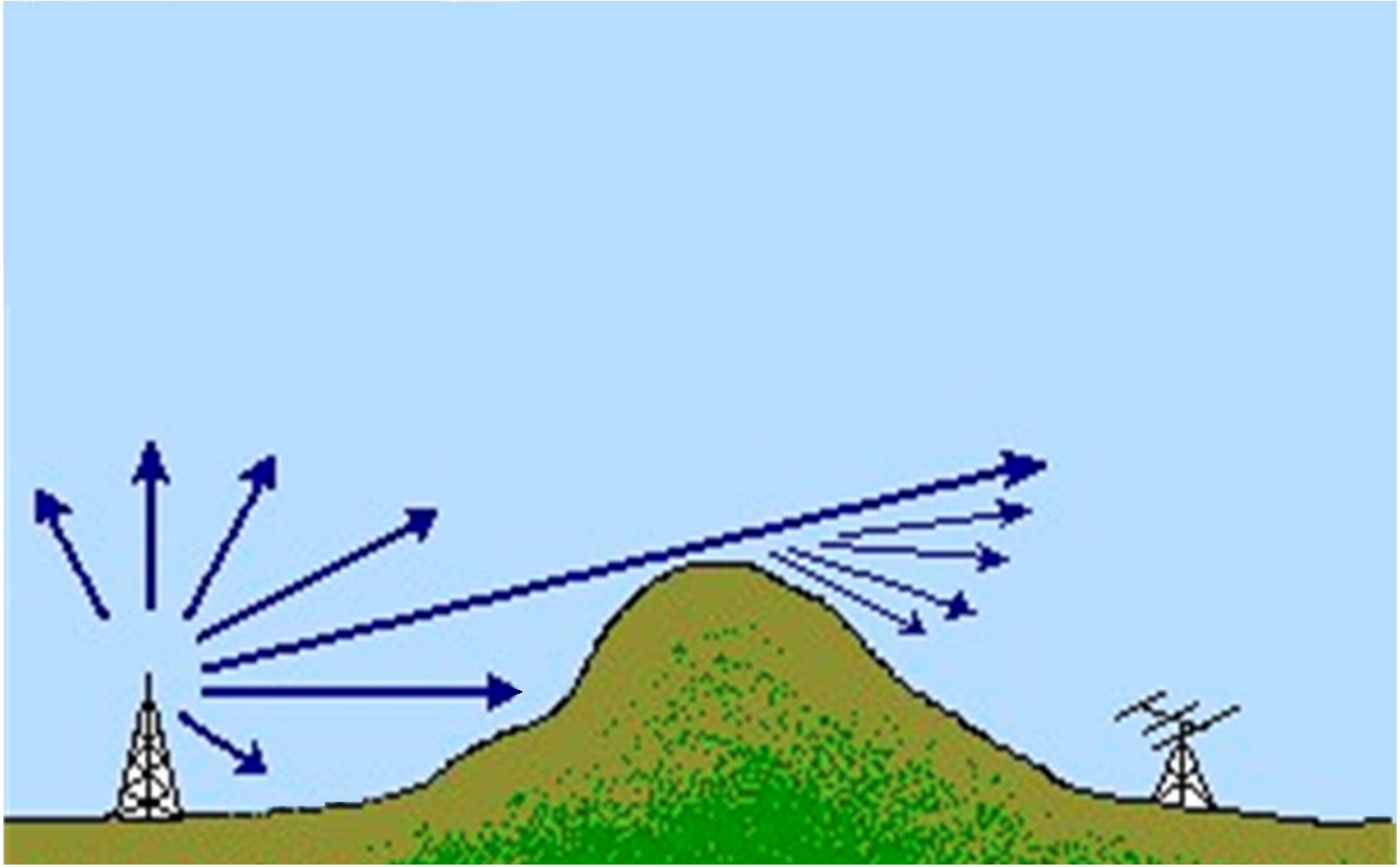
- **The bistatic cross-section is approximately**

$$\sigma_{bistatic}(\theta_t, \theta_r) = \frac{\mu}{\tan^2 \beta_0} \exp\left(-\frac{\tan^2 \theta_t + \tan^2 \theta_r}{2 \tan^2 \beta_0} \right)$$

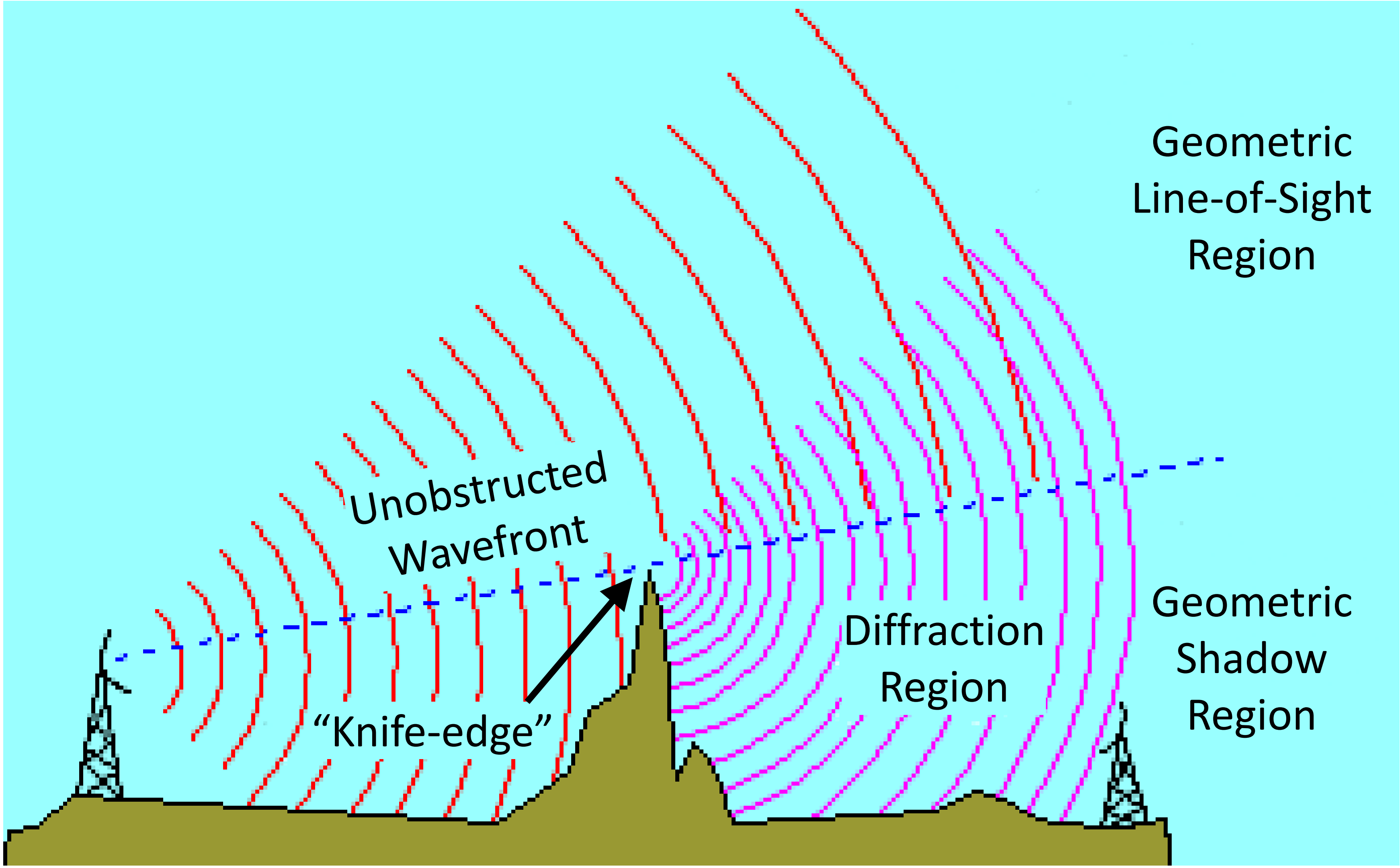
- **Parameters β_0 and μ are tabulated; for urban industrial areas at VHF**

$$\beta_0 = 13° \quad \text{and} \quad \mu = -8\,\text{dB}$$

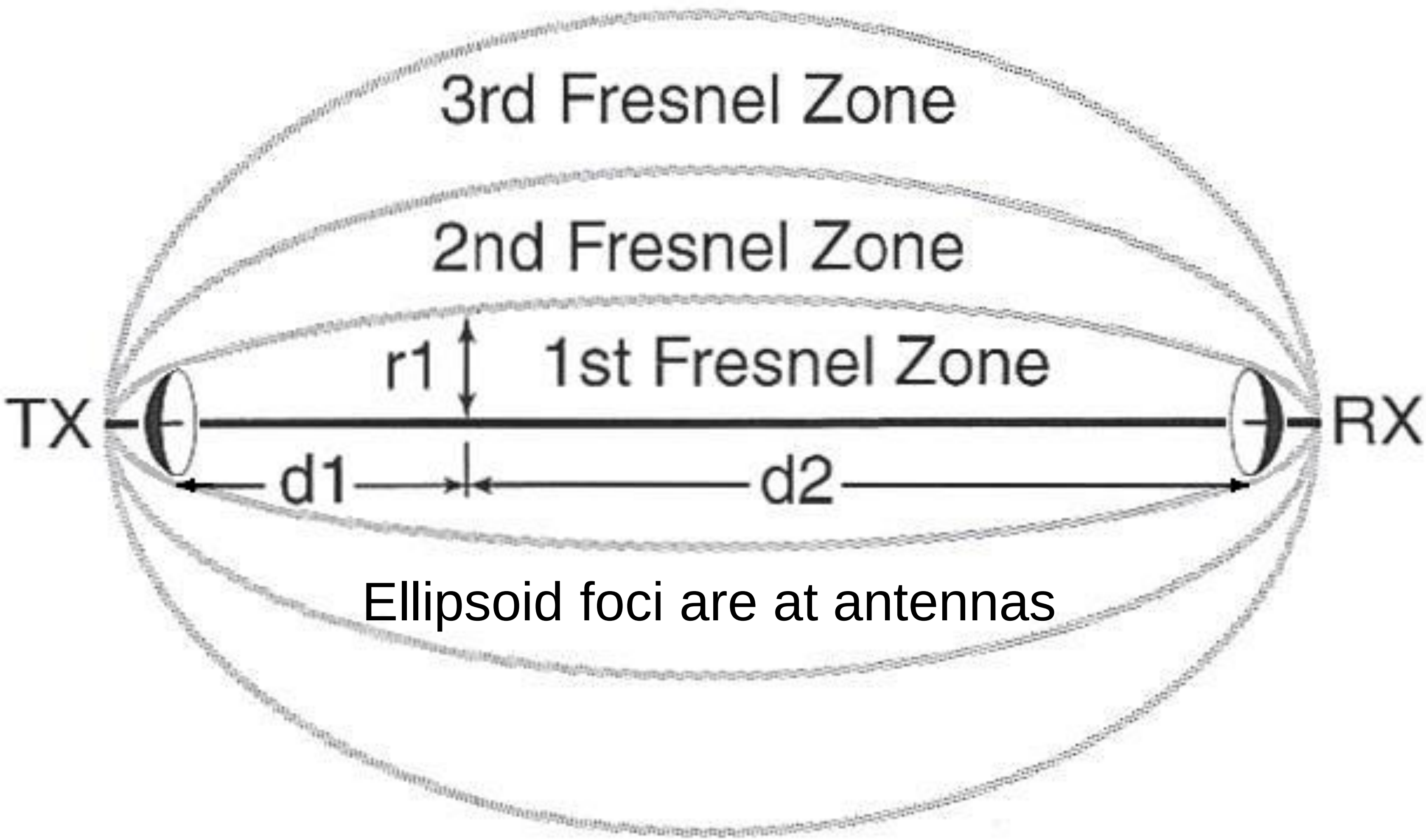
Knife Edge Diffraction – Ray Viewpoint



Knife Edge Diffraction – Wave Viewpoint

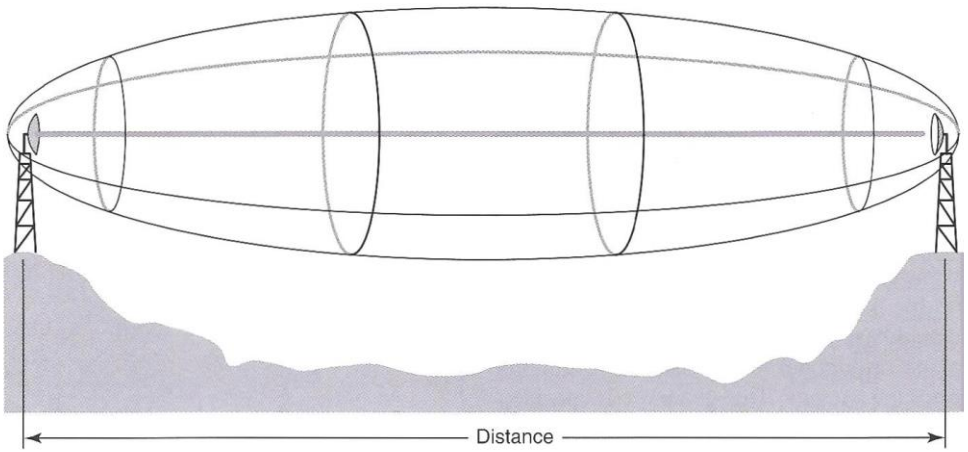


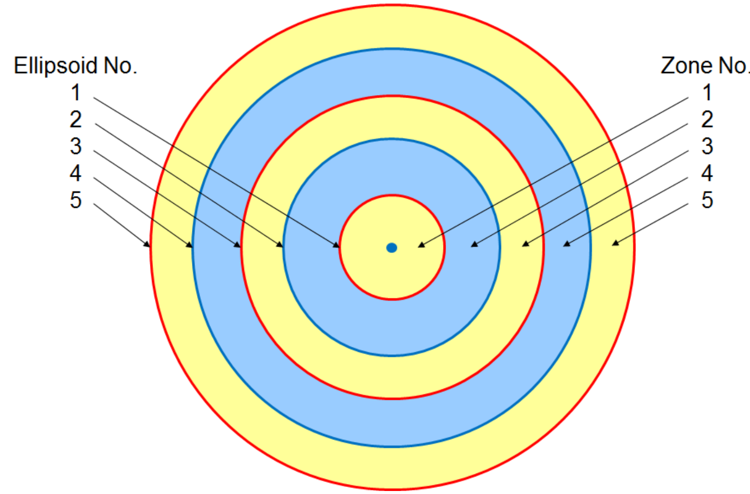
Fresnel Ellipsoids



Ellipsoid foci are at antennas

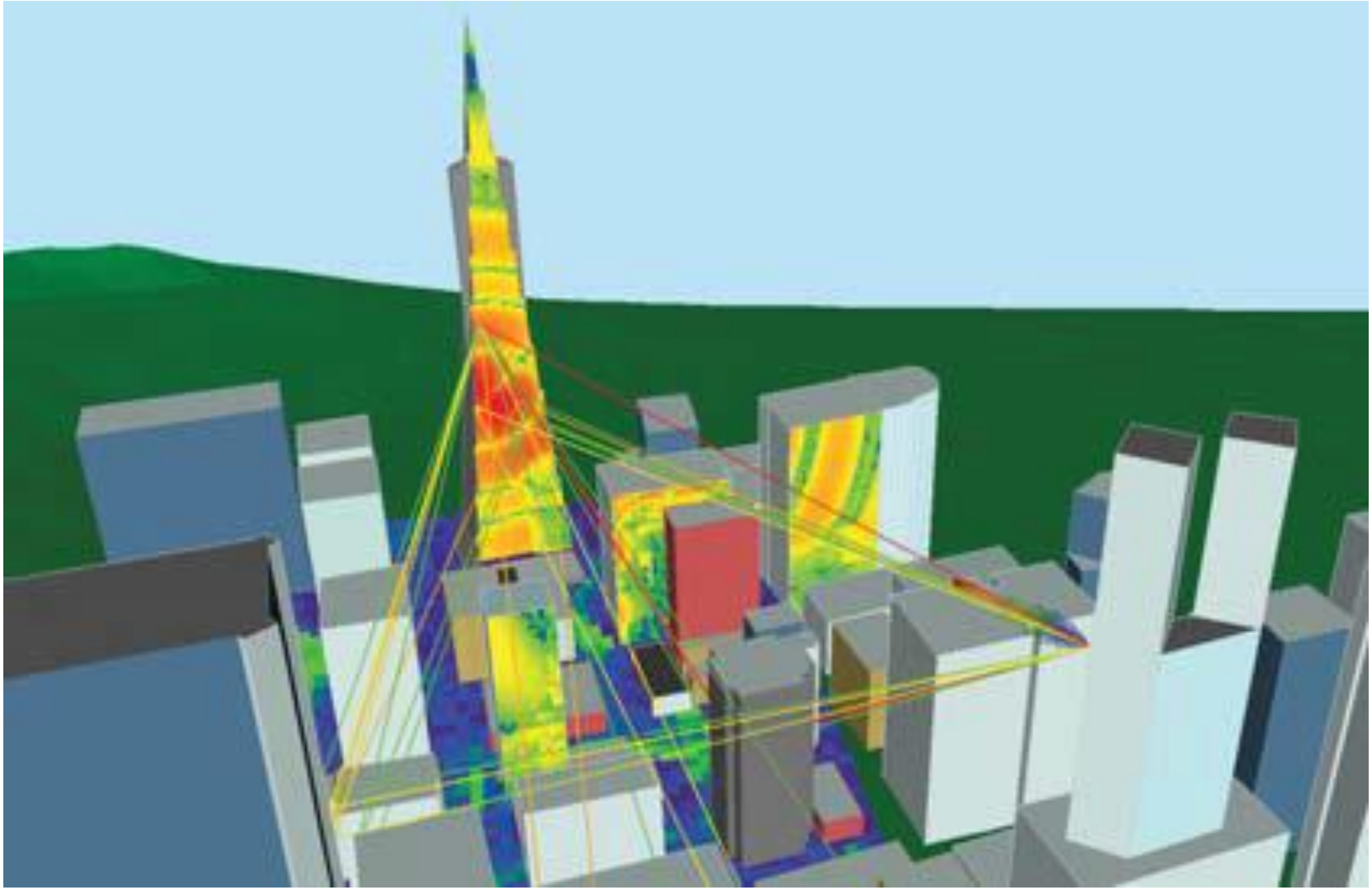
Line-of-Sight Paths Over Irregular Terrain – Rules of Thumb





- **Obstacles (peaks and ridges) along path may extend into the Fresnel zones**
- **Blockages of *even* numbered zones is allowed**
  - Secondary waves created by Huygens principle arrive in phase
- **Blockages of *odd* numbered zones should be avoided**
  - Secondary waves created by Huygens principle arrive out of phase
- **Exact analysis can be done by moment method if terrain geometry and material constants are known**

Physical Optics – Shooting, Bouncing Rays



Courtesy of Remcom

Equation for Link Budget and Service Contour/Coverage Calculation

- **Friis transmission equation**

$$P_r = \frac{P_t\, G_t\, G_r\, \lambda^2\, L_{pol}\, L_r}{(4\pi r)^2}$$

- **Free space path loss is due to geometric spreading**

$$L_{path} = \left(\frac{\lambda}{4\pi r}\right)^2 \quad \Leftrightarrow \quad -36.6 - 20\log_{10} f_{MHz} - 20\log_{10} r_{miles}\ \text{dB}$$

$$L_{pol} = \text{polarization mismatch loss}$$

$$L_r = \text{receiver coupling loss}$$

H.T. Friis, "A Note on a Simple Transmission Formula," *Proc. IRE*, May 1946

Algorithms and Software for VHF/UHF Radio Propagation Analysis

SPLAT!

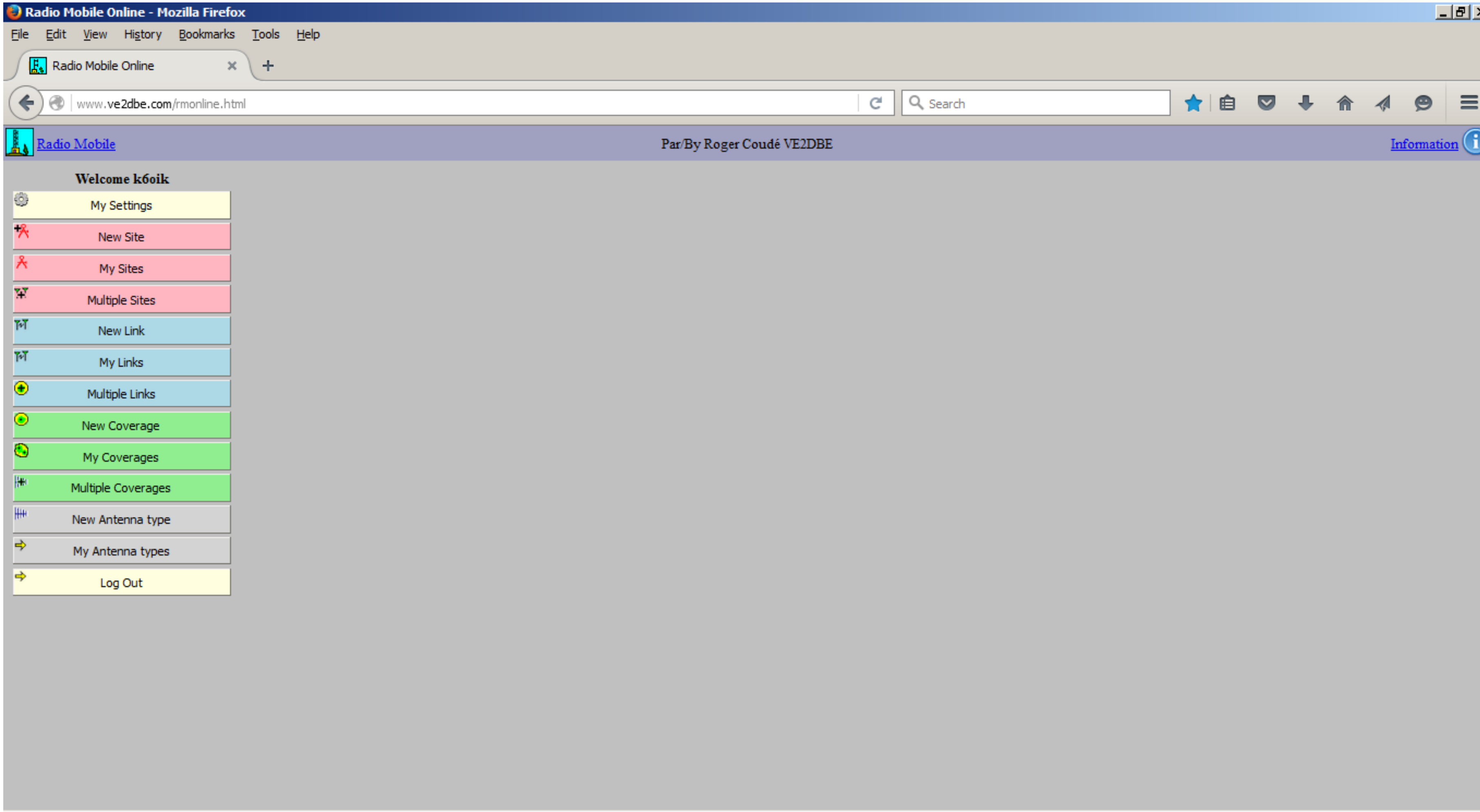
Radio Mobile

Others

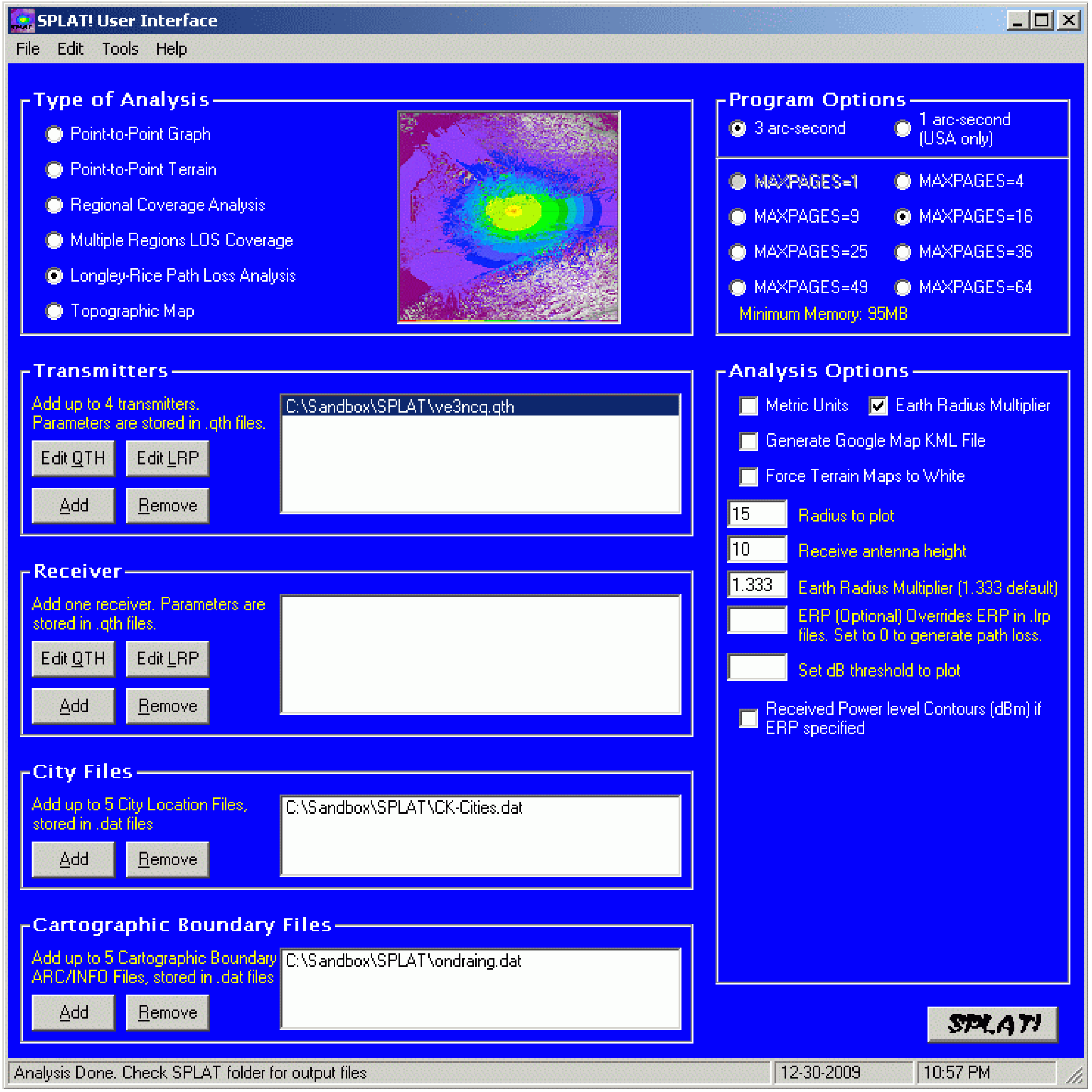
Algorithms for Propagation Prediction for VHF/UHF Link, System, and Cell Planning

- **Physical**
  - Method of Moments (MoM)
  - Uniform Theory of Diffraction (UTD)
  - Geometric Theory of Diffraction (GTD)
  - Physical optics (PO), Geometric Optics (GO), Ray tracing, Shooting and Bouncing Ray (SBR) Method
- **Hybrid**
  - ITU REC P.1546
  - Irregular Terrain with Obstructions Model (ITWOM)
  - Irregular Terrain Model (ITM)
  - A.G. Longley and P.L Rice (1968)
  - J. Epstein and D.W. Peterson (1953)
- **Statistical**
  - COST31
  - Okumura
  - Hata

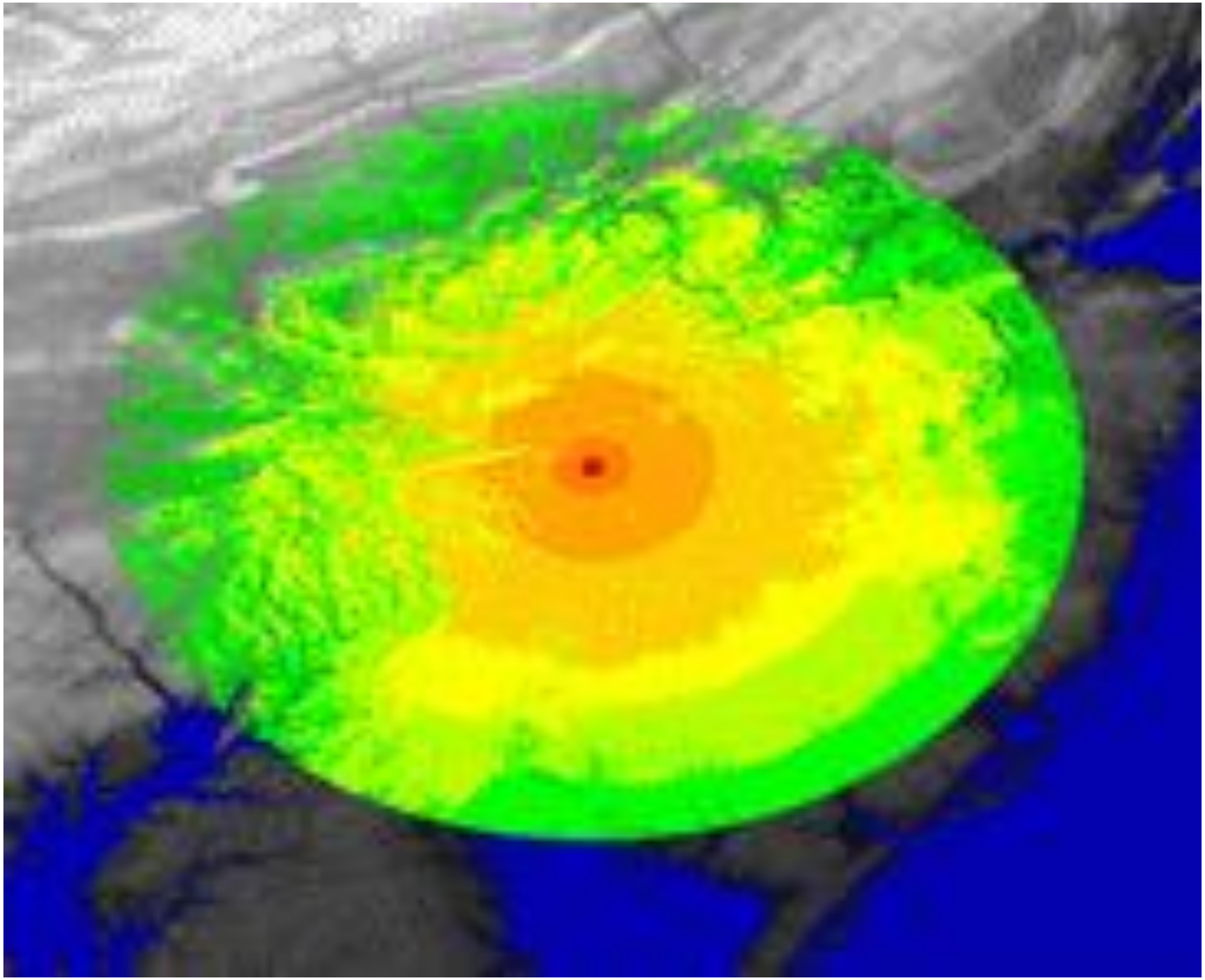
Radio Mobile Online Main Screen



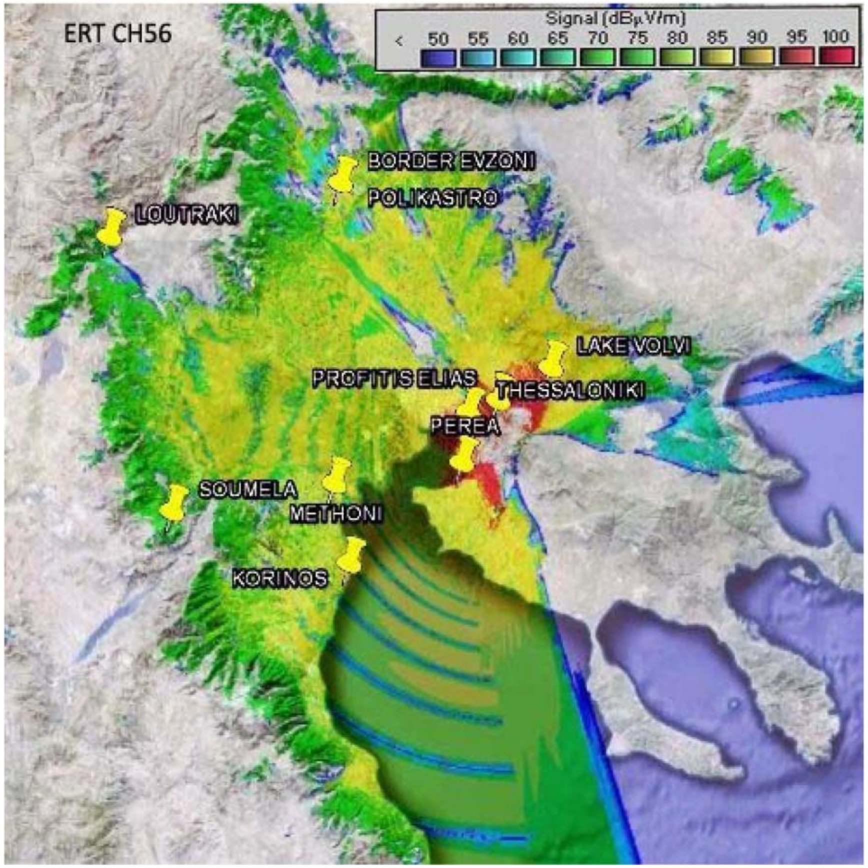
SPLAT!

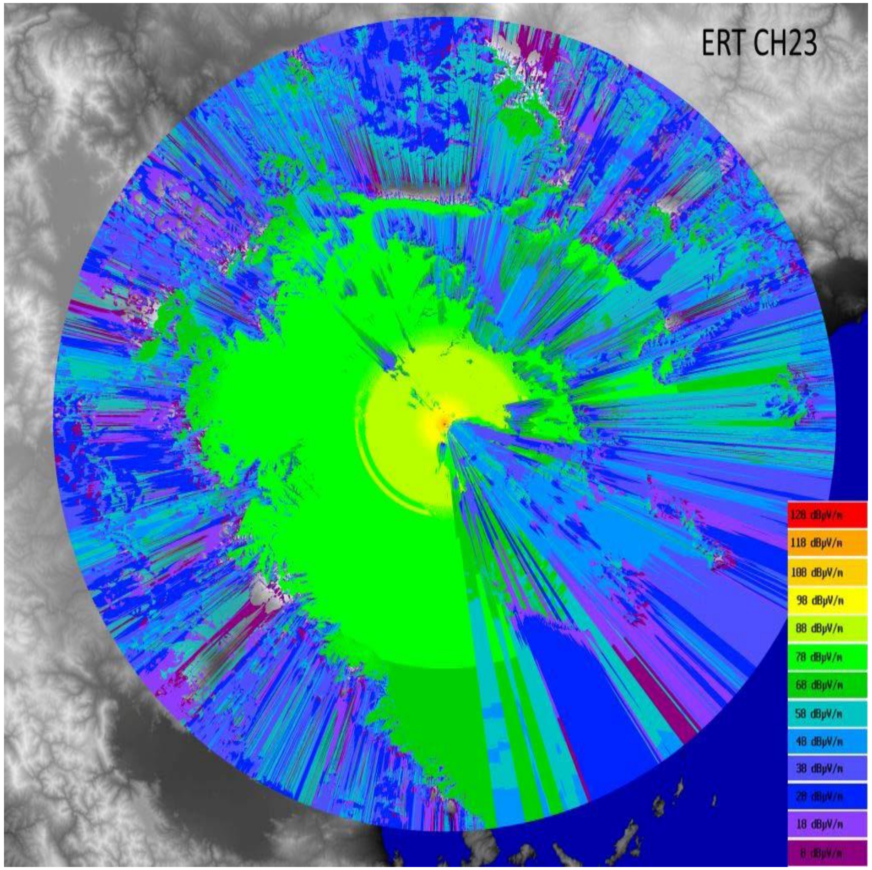

SPLAT! User Interface
File Edit Tools Help
Type of Analysis
Point-to-Point Graph
Point-to-Point Terrain
Regional Coverage Analysis
Multiple Regions LOS Coverage
Longley-Rice Path Loss Analysis
Topographic Map
Program Options
3 arc-second
1 arc-second (USA only)
MAXPAGES=1
MAXPAGES=4
MAXPAGES=9
MAXPAGES=16
MAXPAGES=25
MAXPAGES=36
MAXPAGES=49
MAXPAGES=64
Minimum Memory: 95MB
Transmitters
Add up to 4 transmitters. Parameters are stored in .qth files.
C:\Sandbox\SPLAT\ve3ncq.qth
Edit QTH
Edit LRP
Add
Remove
Receiver
Add one receiver. Parameters are stored in .qth files.
Edit QTH
Edit LRP
Add
Remove
City Files
Add up to 5 City Location Files, stored in .dat files
C:\Sandbox\SPLAT\CK-Cities.dat
Add
Remove
Cartographic Boundary Files
Add up to 5 Cartographic Boundary ARC/INFO Files, stored in .dat files
C:\Sandbox\SPLAT\ondraing.dat
Add
Remove
Analysis Options
Metric Units
Earth Radius Multiplier
Generate Google Map KML File
Force Terrain Maps to White
15
Radius to plot
10
Receive antenna height
1.333
Earth Radius Multiplier (1.333 default)
ERP (Optional) Overrides ERP in .lrp files. Set to 0 to generate path loss.
Set dB threshold to plot
Received Power level Contours (dBm) if ERP specified
SPLAT!
Analysis Done. Check SPLAT folder for output files
12-30-2009
10:57 PM

Example of SPLAT! Coverage Depiction



Radio Mobile versus SPLAT!





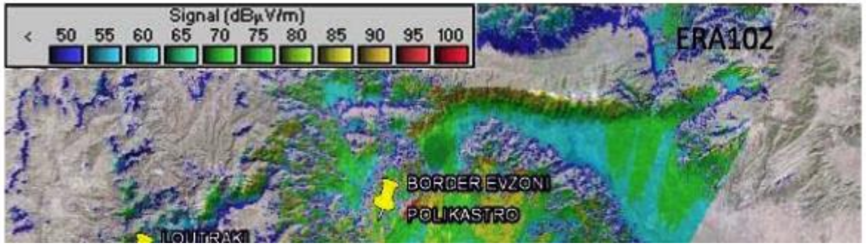
Comparison by Kasampalis, et al., 2013

SPLAT! (ITM) than Radio Mobile. Consequently, Radio Mobile gives better simulation results with a lower standard deviation (S.D. = 7.2dB) than SPLAT! for Windows (S.D.= 16.2 dB), though both software use ITM for propagation modeling. It can be also seen in the FM case that the simulations results produced by SPLAT! for Windows are worse than Radio Mobile results, and getting worse as distance increases above around 40Km. The simulation results are, in general worse for VHF FM radio frequencies than those for UHF DVB-T frequencies.

Differences between FSH-3, SPLAT! for Windows with ITM and SPLAT! v 1.4.0 for Linux with ITWOM, with average error and standard deviation , are shown in Table VI. Errors between measurements (FSH-3) and simulations (SPLAT!-ITM & SPLAT!-ITWOM), are shown in the bar graph below, Fig. 7.

measurement points using SPLAT! with ITWOM are better than SPLAT! for Windows, which in turn gives better results for No. 1 and 2 measurement points. We observe that for frequencies in the VHF FM range, SPLAT! with ITWOM gives better simulation results than SPLAT! for Windows.

A coverage map produced by Radio Mobile (ITM Model) for Greek public FM radio "ERA-102" is shown in Fig. 8. A coverage map produced by SPLAT! for Windows (splat-1.2.3-win32) for the Greek Public FM Radio Station, "ERA-102" is shown in Fig. 9.



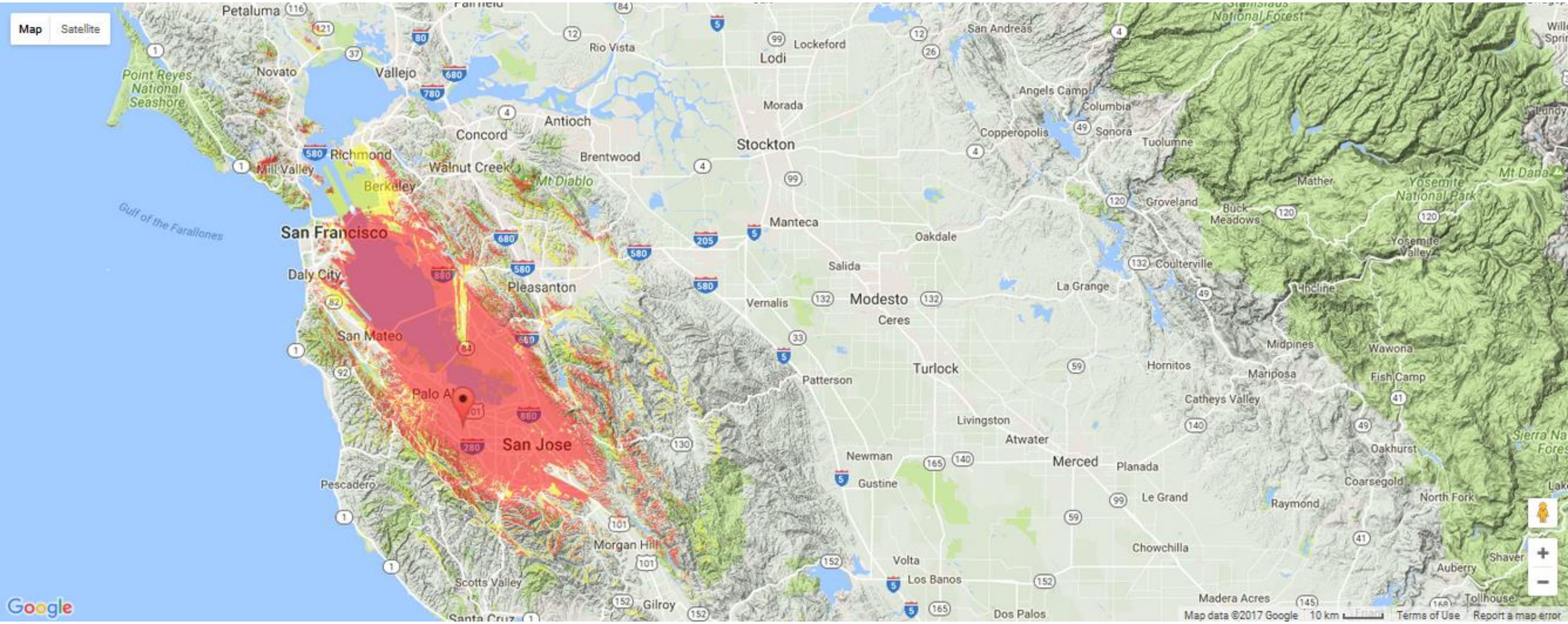
SPECS Repeater Coverage

Repeater System Parameters

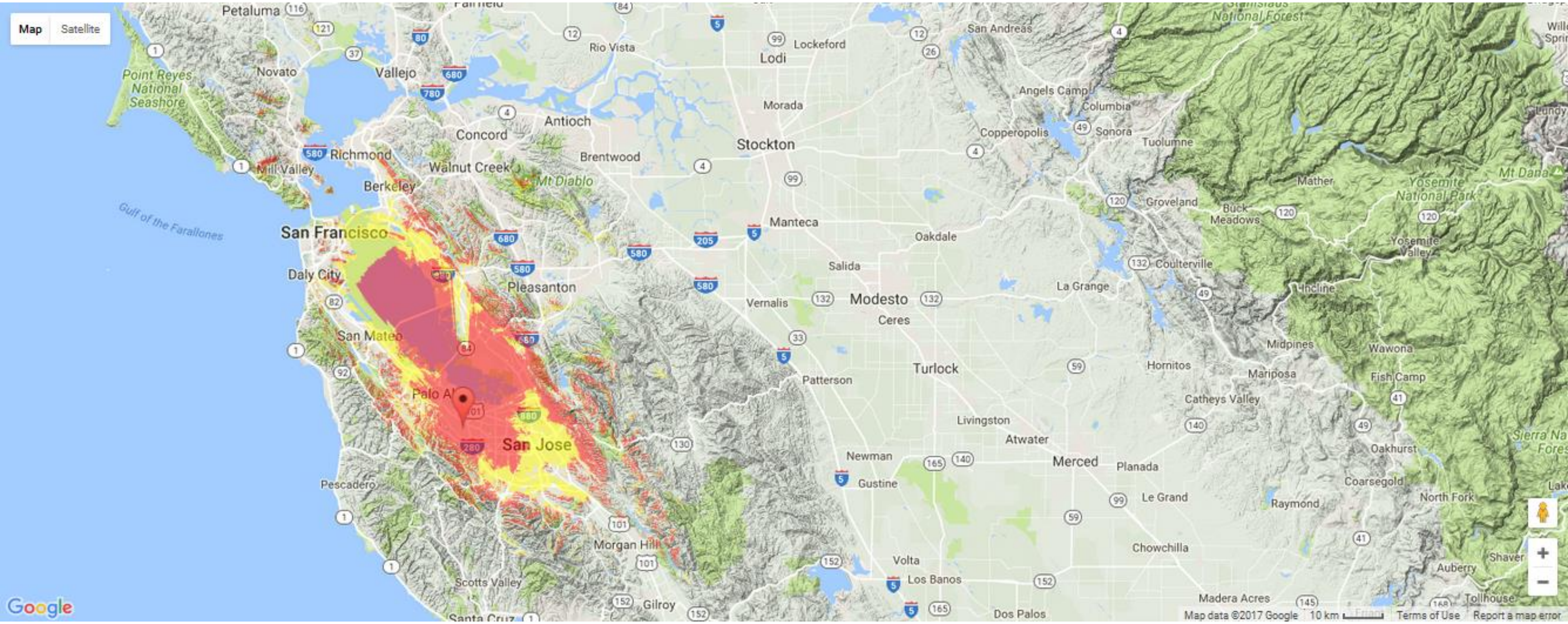
Parameter	2-meter machine	1.25-meter machine	70-cm machine
Frequency	**145.270 MHz**	**224.140 MHz**	**440.800 MHz**
Latitude	**37.368127**	**37.368068**	**37.368287**
Longitude	**-122.080242**	**-122.080344**	**-122.080265**
Elevation (building roof)	**75.3**	**75.3**	**78.3**
Antenna height above roof	**24 ft/7.3 m to ant ctr. 17 ft/5 m to ant btm.**	**1.83 m**	**2.62 m**
HAAT (to antenna center)	95 ft.	75 ft.	100 ft.
Antenna model	Hustler G7-144	Comet CA-Super22	Hustler G6-440
Antenna type	15.33 ft. vertical GP	8 ft. vertical GP	7.25 ft. vertical GP
Antenna gain	**9.15 dBi (7.0 dBd)**	**6.6 dBi (4.85 dBd)**	**8.15 dBi (6.0 dBd)**
Antenna SWR	1.5	1.5	1.5
Tx Power into duplexer	**33 W**	**28 W**	**25 W**
Duplexer loss	**1.6 dB**	**1.4 dB**	**1.0 dB**
Cable type	Heliax LDF4-50A	Heliax LDF4-50A	Heliax LDF5-50A
Cable length	60 ft.	60 ft.	70 ft.
Cable matched loss	0.482 dB	0.603 dB	0.558 dB
Cable loss at SWR = 1.5	**0.519 dB**	**0.658 dB**	**0.638 dB**
Antenna mismatch loss	**0.18**	**0.18**	**0.18**
Coax connector loss	**1 dB**	**1 dB**	**1 dB**
Total loss	**3.299**	**3.238**	**2.818**
Power into antenna	**15.44 W**	**13.28 W**	**13.07 W**
Receiver sensitivity	< 0.1 μV	< 0.1 μV	< 0.1 μV

Pause for Demonstration

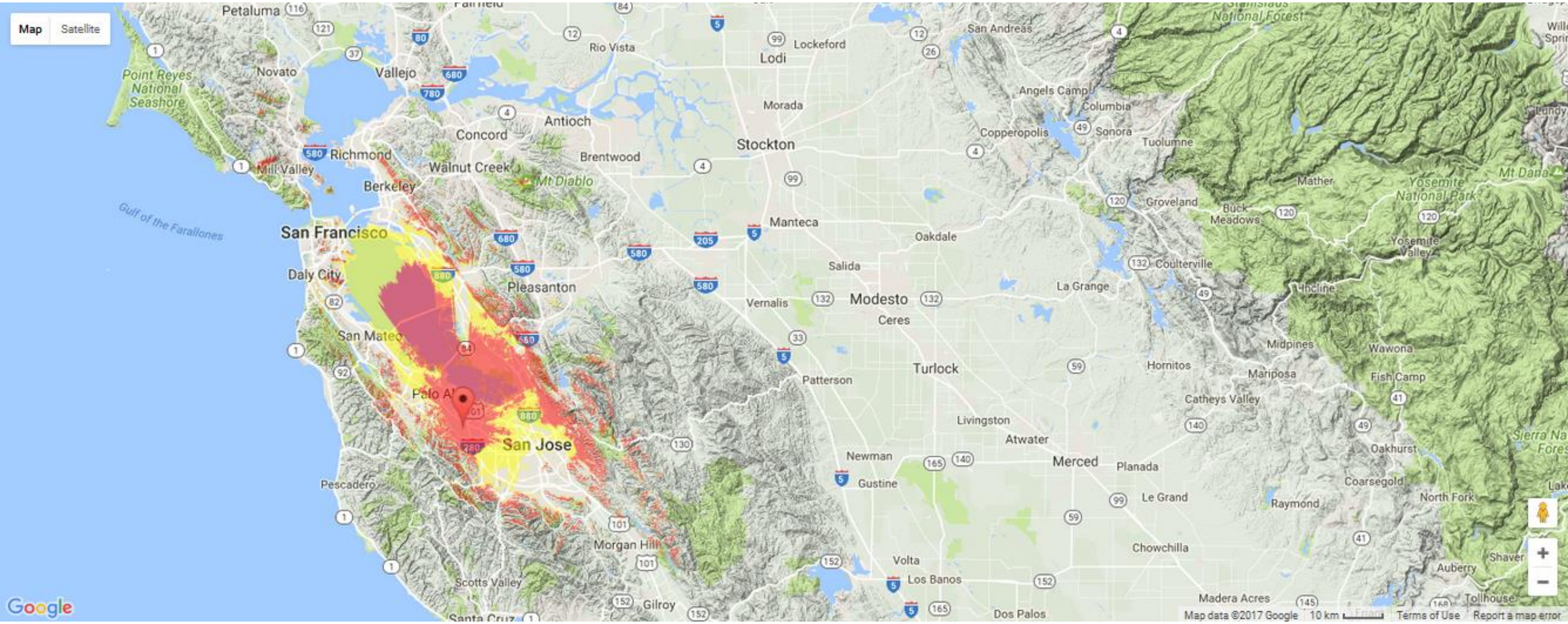
W6ASH 2-Meter Coverage from a 5-W HT



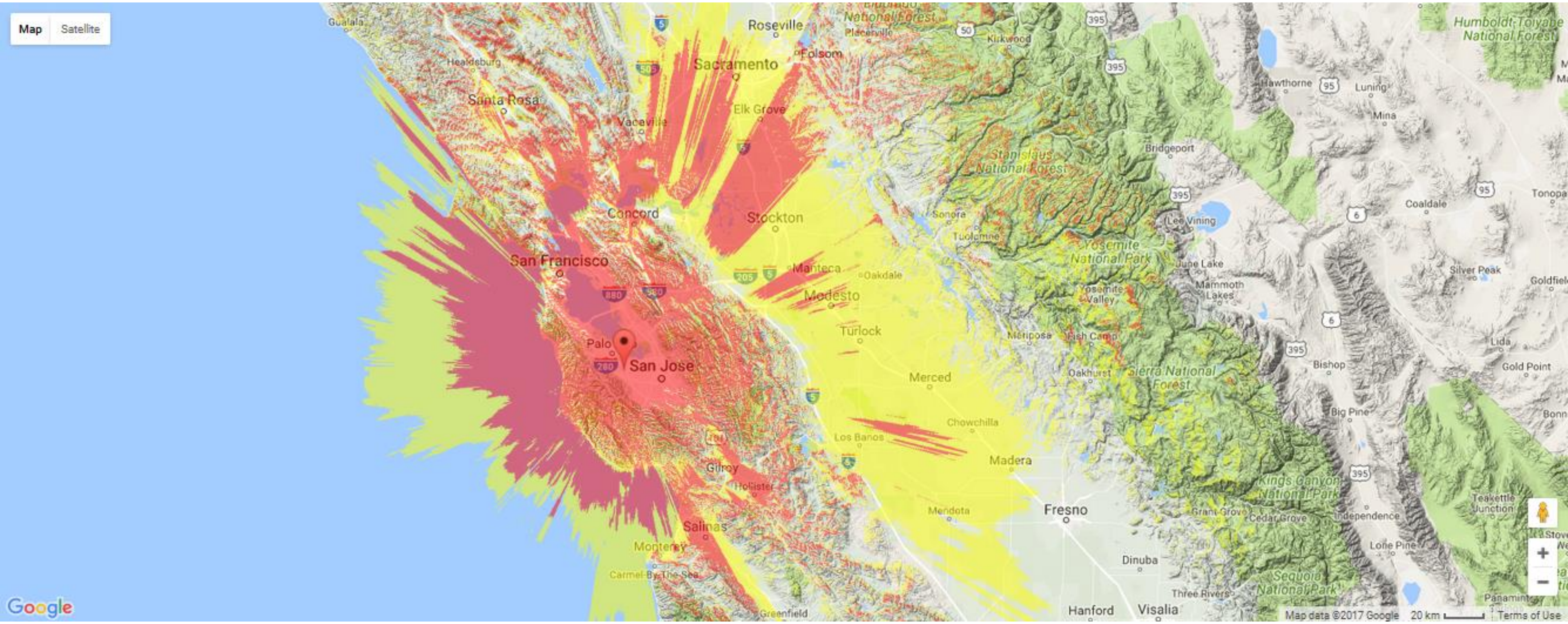
W6ASH 1.25-Meter Coverage from a 5-W HT



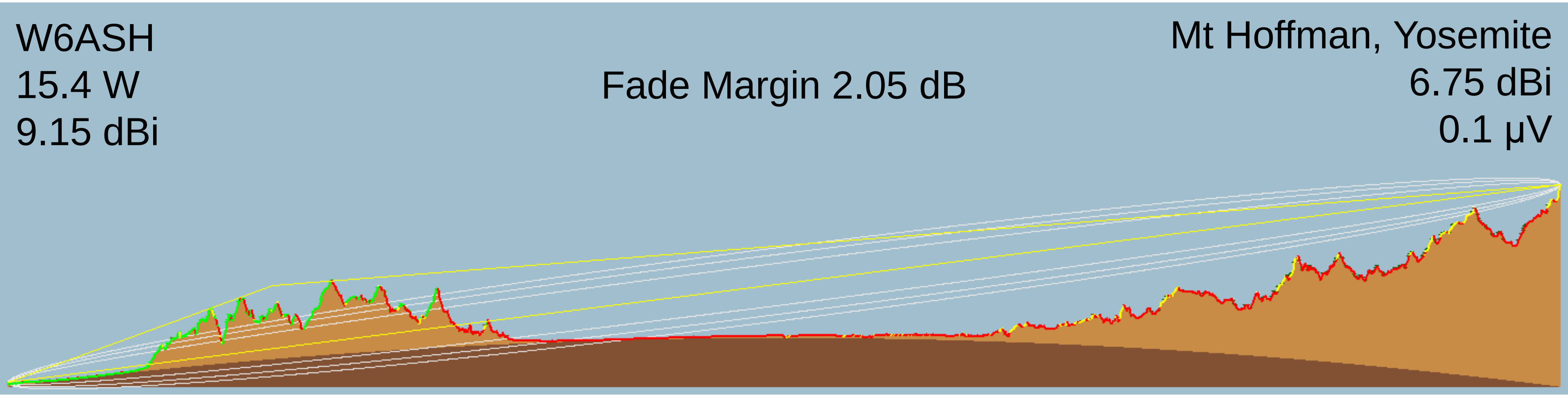
W6ASH 70-cm Coverage from a 5-W HT

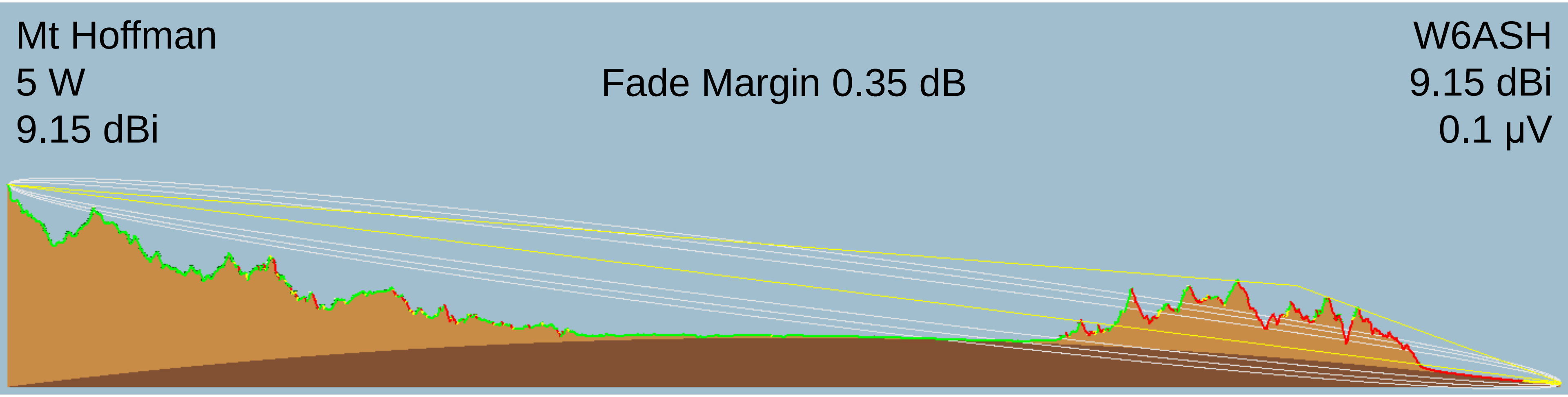


W6ASH 2-Meter DX Coverage, 15.4 W, 80% Probability



W6ASH to Yosemite (and Back) on 2 meters





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The End

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