Hardware Demonstration:

Radiated Emissions as a Function of Common Mode Current
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Acronyms

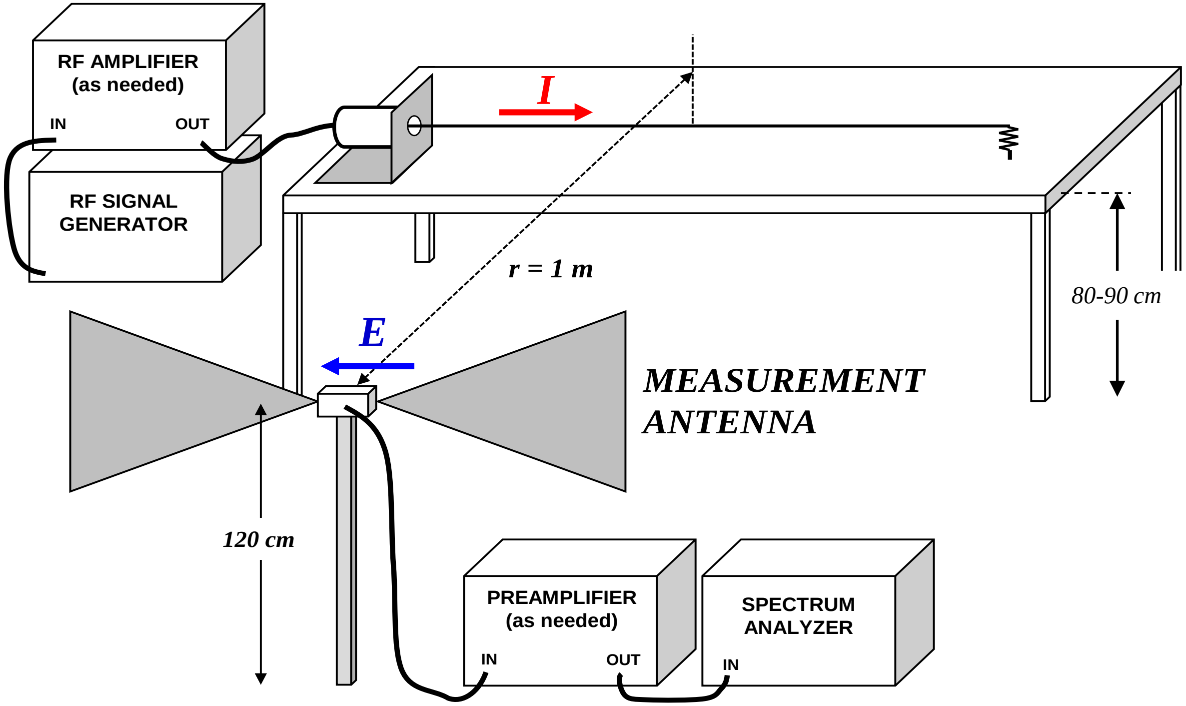
- **Common mode conducted emissions (CMCE)**
- **Conducted emissions (CE)**
- **Electric field per unit current (E/I)**
- **Electromagnetic interference (EMI)**
- **Equipment under test (EUT)**
- **Radiated emissions (RE)**

Introduction (1 of 3)

- Due to the time- and resource-consuming nature of the test for radiated emissions, electric field (RE02/RE102), it is often prohibitive to perform early diagnostics by performing the test or even an abbreviated version of it
- Fortunately, it is possible to perform a much simpler, cheaper test – a common mode conducted emissions (CMCE) test – which will give useful predictions for much less expenditure of time and money
- The CMCE measurement can be easily performed in the hardware development lab in order to provide an early indication of whether the Equipment Under Test (EUT) will pass the RE102 test before the EUT is taken to a full EMI test facility

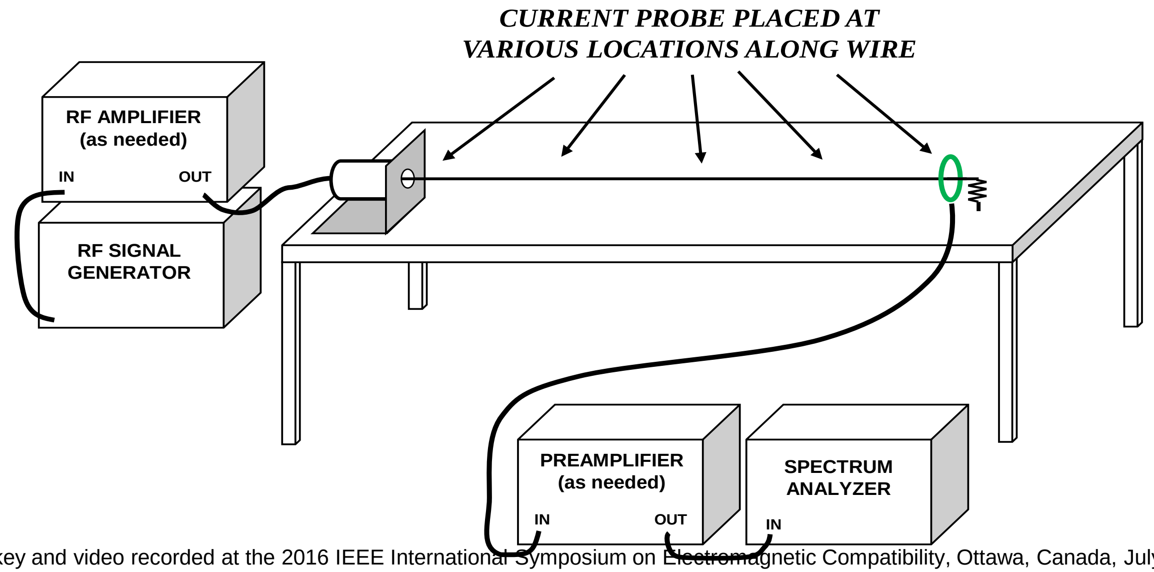
Introduction (2 of 3)

- At frequencies below 200 MHz, a significant portion of the radiated energy originates from uncontrolled common mode currents on cables connected to the unit
- In this demonstration, a controlled current is applied to a 1 m wire 5 cm above a ground plane, and the resulting electric field is measured

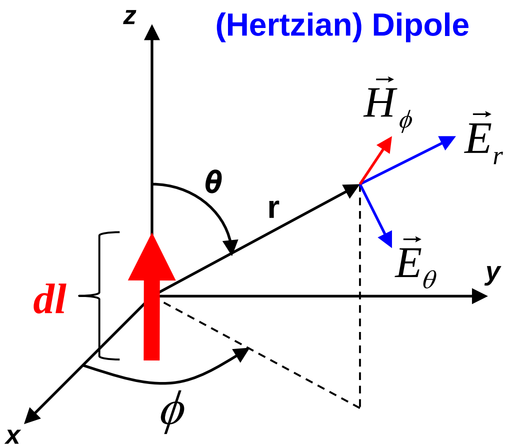


Introduction (3 of 3)

- **The transfer function of electric field per unit current (E/I) is determined**
  - Presented as a tool for predicting radiated electric fields from a simple measurement with a clamp-on current probe before the product ever leaves the development laboratory
  - |*E*/*I*| correspondence is evaluated at frequencies $\geq$ 30 MHz
  - Per MIL-STD-461, RE102 below 30 MHz is measured with rod antenna, which responds to potential, not current
- **Product development engineers are encouraged to perform these measurements in order to facilitate diagnosis of potential problems as early as possible in the product's development cycle**



Electric Field from Elemental Electrical (Hertzian) Dipole



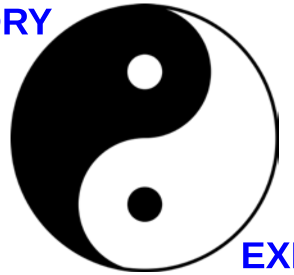
Wavenumber:

$$\beta_0 = \frac{2\pi}{\lambda} = \frac{2\pi f}{c}$$

$$E_\phi = 0$$

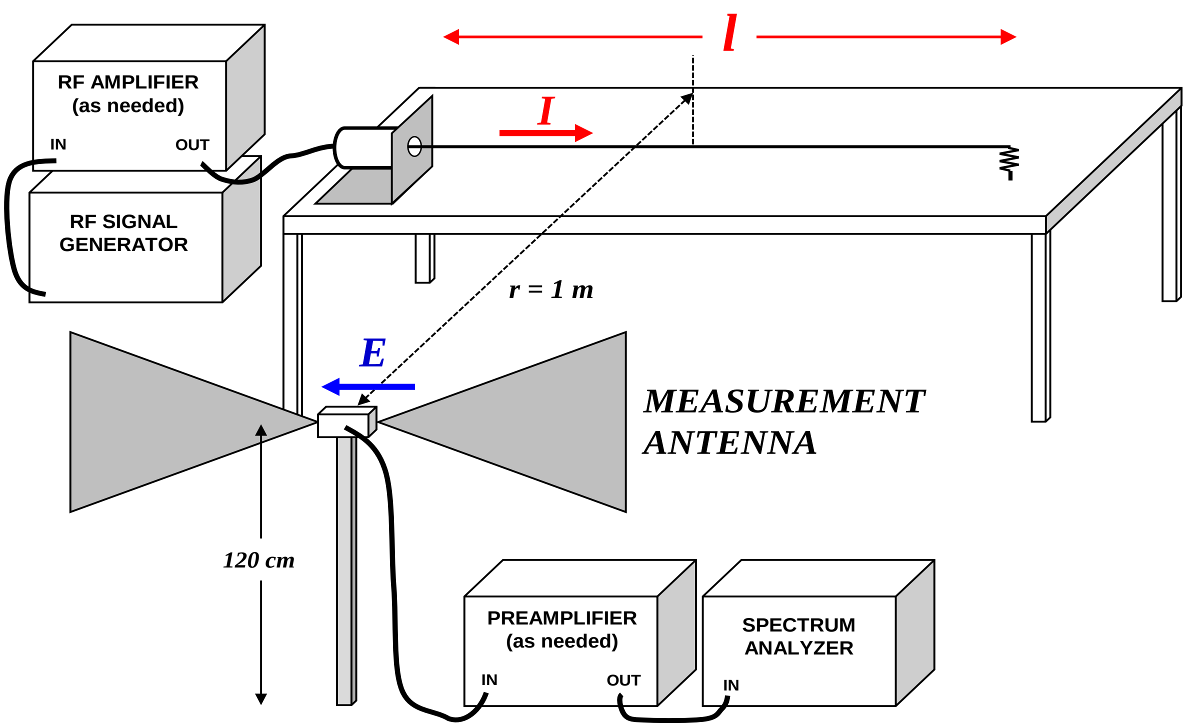
$$E_r = 2\frac{Idl}{4\pi}\eta_0\beta_0^2\cos\theta\left(\frac{1}{\beta_0^2 r^2} - j\frac{1}{\beta_0^3 r^3}\right)e^{-j\beta_0 r}$$

$$E_\theta = \frac{Idl}{4\pi}\eta_0\beta_0^2\sin\theta\left(j\frac{1}{\beta_0 r} + \frac{1}{\beta_0^2 r^2} - j\frac{1}{\beta_0^3 r^3}\right)e^{-j\beta_0 r}$$



A Very Sick Integral

- For a wire of any finite length, a precise calculation of the electric field at distance r would require a very complex integral
- Distance to measurement point must be varied with location of *dl* along the wire
- Relative phase of each field contribution must be considered
- Vector contributions of E_r and E_θ
- Etc., etc., etc.



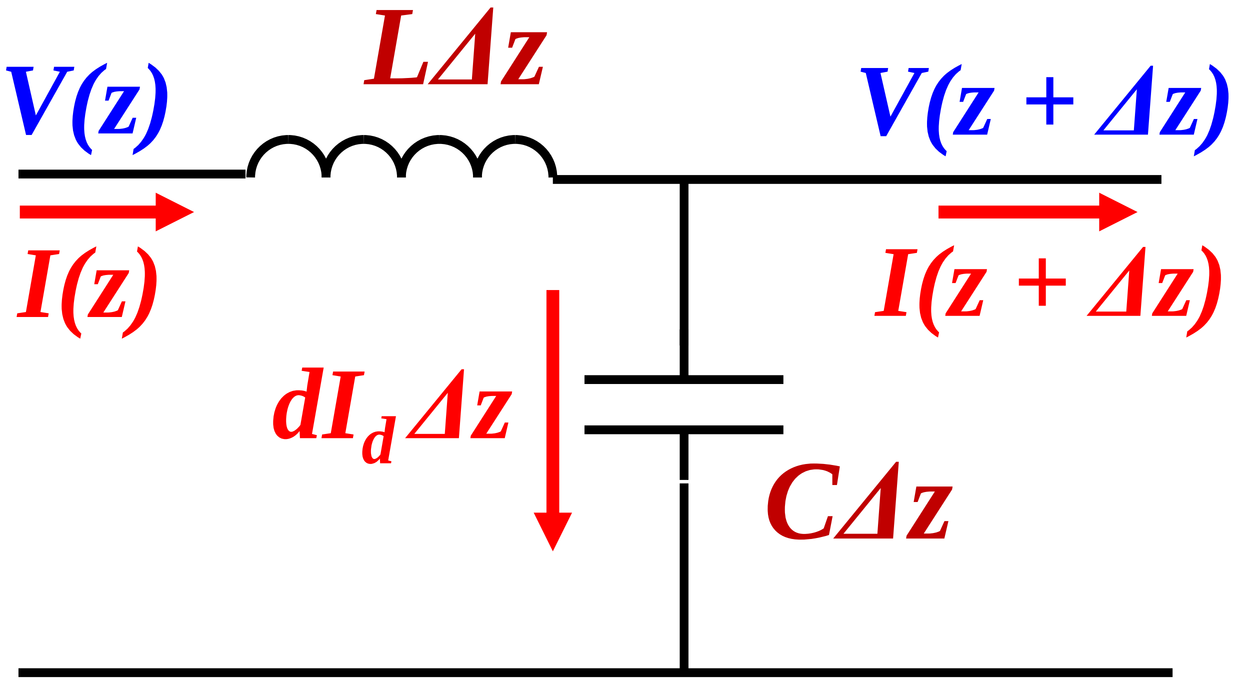
Simplifying Assumptions for |E/I| Envelope

- **Measurement is in traditional definition of "far field"**
  - *$\beta r > 1$ (f > 48 MHz for r = 1 m; generally OK for f > 30 MHz*)
  - *$1/\beta r$* term dominates
  - *$1/(\beta r)^2$* and *$1/(\beta r)^3$* terms may be neglected
- **Cable behaves as a point source for estimating worst-case envelope**
  - All current carrying elements are assumed to be at the same distance r from the measurement point
  - The electric field contributions from all current-carrying elements are assumed to be in phase at the measurement point

$$\left|\frac{E_{max}}{I}\right| \approx \frac{\mu_0 l f}{2r}$$

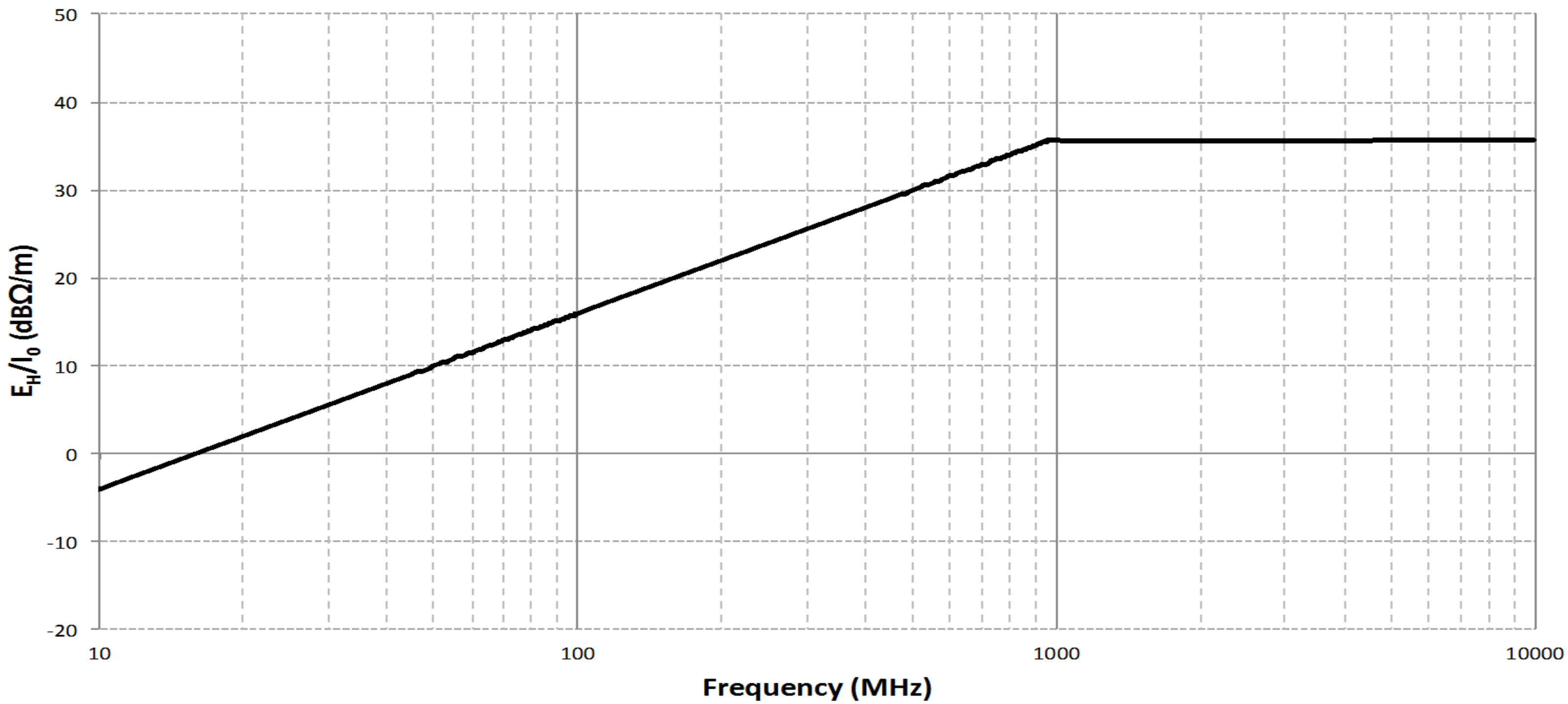
Transmission Line Current Model

- **Transmission line current has horizontal and vertical components**
- **Resulting electric field will have horizontal and vertical components**

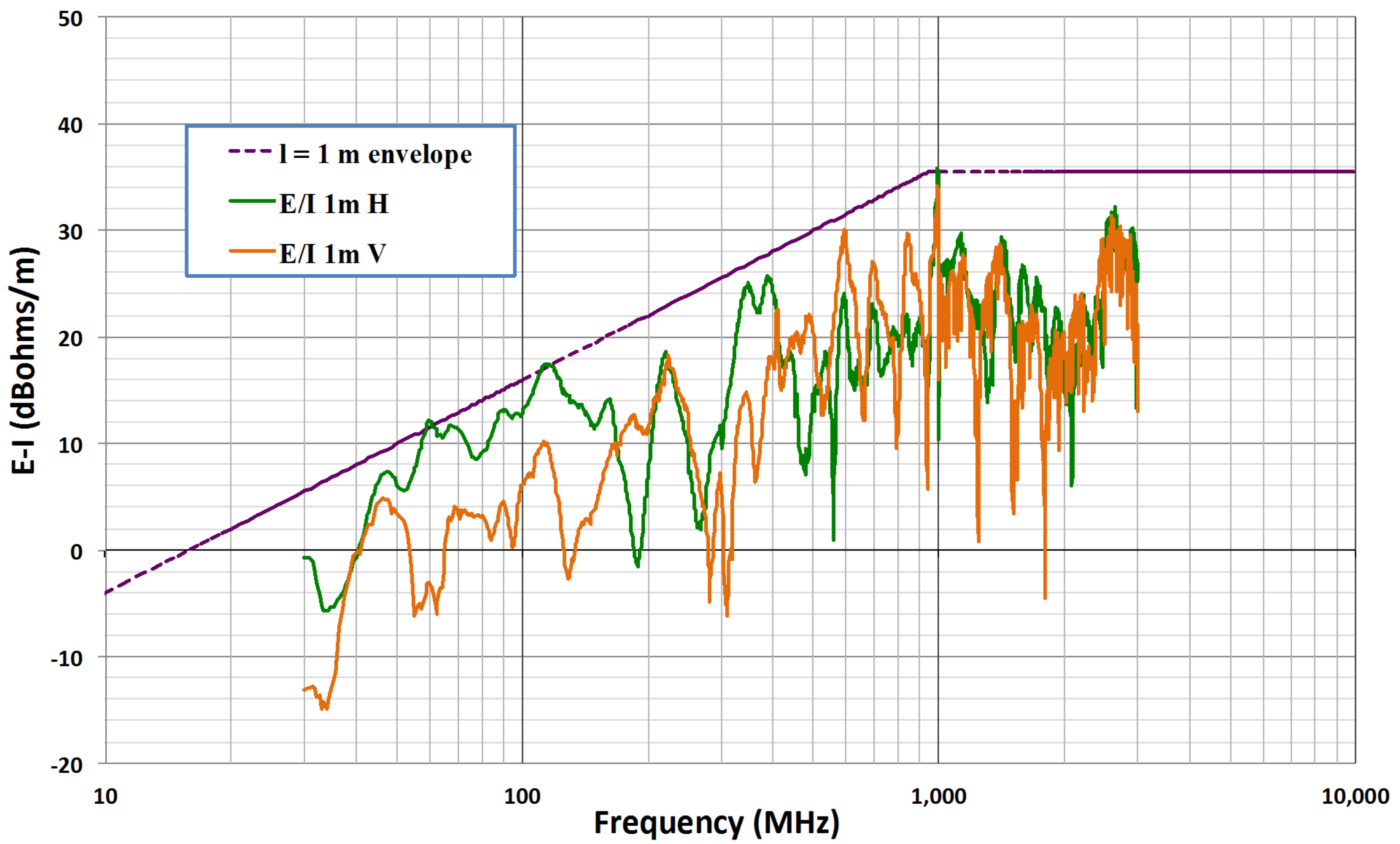


|E/I| Envelope for Wire 5 cm Above Ground Plane

- **Math in backup charts, but here's the bottom line:**
  - Horizontal polarization
    - For cables of $l > 1\ m$ (typical on most spacecraft), |E/I| is essentially independent of wire length above 48 MHz ($\beta l > 1$)
    - For most spacecraft, RE102 is mainly a concern for *f* ≥ *200 MHz*
    - High frequency asymptote determined largely by interaction of cable with ground plane (details in backup slides)
  - Vertical polarization
    - |E/I| is essentially independent of wire length for *f* ≥ *30 MHz*
    - Equivalent to |E/I| for horizontal polarization for wire of $l = 1\ m$
    - High frequency asymptote determined by monopole formed between cable and ground plane (details in backup slides)



|E/I| Measured vs. Predicted

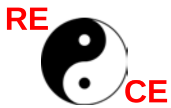


Current Measurement Helpful Hint

- **For *f* > *30 MHz*, cables of *l* > *1 m* will exhibit standing waves**
  - Current will NOT be constant along length
  - Note that |E/I| is based on integrated, i.e. average, current along cable
- **Traditional approach**
  - Place spectrum analyzer in max hold mode
  - Physically scan probe along length of cable
  - Relatively quick and easy, but this will give the peak current on cable, not average
  - Will overestimate current and electric field
- **Recommended approach**
  - Measure current at many locations along wire
  - Take average
  - If measuring in dB, convert to numeric first

Summary

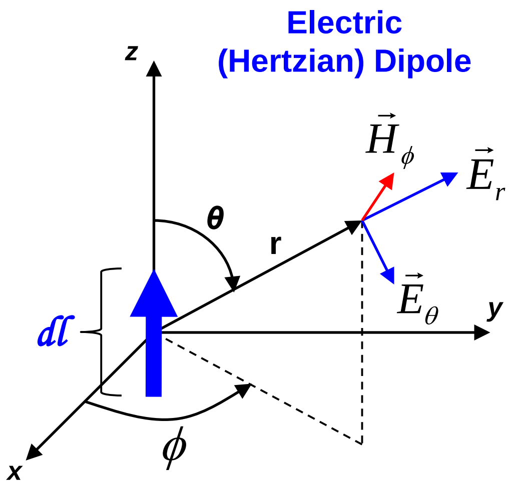
- **Radiated emissions and conducted emissions "joined at the hip"**



- **|E/I| transfer function envelope provides useful tool for predicting radiated emissions early in product development cycle**
- **The current probe is your friend; measure those common mode currents early and often**
  - Easy and useful measurement to make in hardware development lab before taking product to EMI facility
  - Don't have to fight RF background, room resonances, etc.
  - Identify specific sources of potential problems as early as possible
- **Control those common mode currents**
  - Provide the desired low impedance path (e.g. shield, ground plane, etc.) and make them flow where you want them to
  - Let nature do the work
- **When you control common mode currents, you go a long way toward controlling radiated emissions and most other EMI problems**

Backup

Electric Field as Function of Current (Electrically Short Cable, Hertzian Dipole Model)



$$E_\theta = \frac{Idl}{4\pi}\eta_0\beta_0^2 \sin\theta\left(j\frac{1}{\beta_0 r} + \frac{1}{\beta_0^2 r^2} - j\frac{1}{\beta_0^3 r^3}\right)e^{-j\beta_0 r}$$

$$\frac{|E_\theta|_{\max}}{I} = \frac{dl}{4\pi}\eta_0\beta_0^2\sqrt{\left(\frac{1}{\beta_0^2 r^2}\right)^2 + \left(\frac{1}{\beta_0 r} - \frac{1}{\beta_0^3 r^3}\right)^2}$$

Far field approximation ($\beta_0 r > 1$):

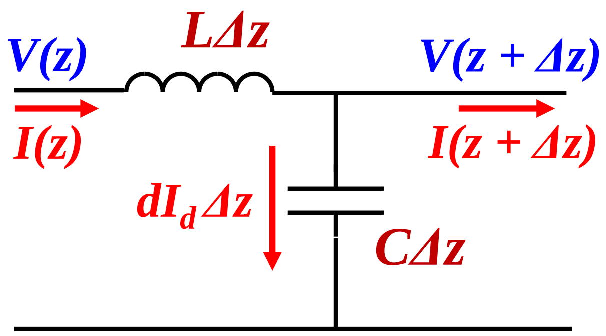
$$\frac{|E_\theta|_{\max}}{I} \approx \frac{l}{4\pi}\eta_0\beta_0^2\sqrt{\left(\frac{1}{\beta_0 r}\right)^2} = \frac{l}{4\pi r}\eta_0\beta_0$$

But: $\beta_0 = \frac{2\pi}{\lambda} = \frac{2\pi f}{c} = 2\pi f\sqrt{\mu_0\varepsilon_0}$ ***and*** $\eta_0 = \sqrt{\frac{\mu_0}{\varepsilon_0}}$ ➡ $\eta_0\beta_0 = 2\pi f\sqrt{\mu_0\varepsilon_0}\cdot\sqrt{\frac{\mu_0}{\varepsilon_0}} = 2\pi f\mu_0$

$$\frac{|E_\theta|_{\max}}{I} \approx \frac{l}{4\pi r}2\pi f\mu_0$$

$$\boxed{\frac{|E_\theta|_{\max}}{I} \approx \frac{\mu_0 l}{2r} f}$$

Transmission Line Currents



$$I(z) = I_0 e^{-j\beta z}$$

$$I(z) = I_0 \cos\beta z$$

Horizontal:

$$I_H = \frac{1}{l}\int_0^l I_0 \cos\beta z dz = \frac{I_0}{\beta l}\sin\beta z\Big|_0^l = I_0 \frac{\sin\beta l}{\beta l}$$

$$\beta l \le 1: \quad \left|\frac{I_H}{I_0}\right|_{ENV} = 1$$

$$\beta l \ge 1: \quad \left|\frac{I_H}{I_0}\right|_{ENV} = \frac{1}{\beta l}$$

Vertical:

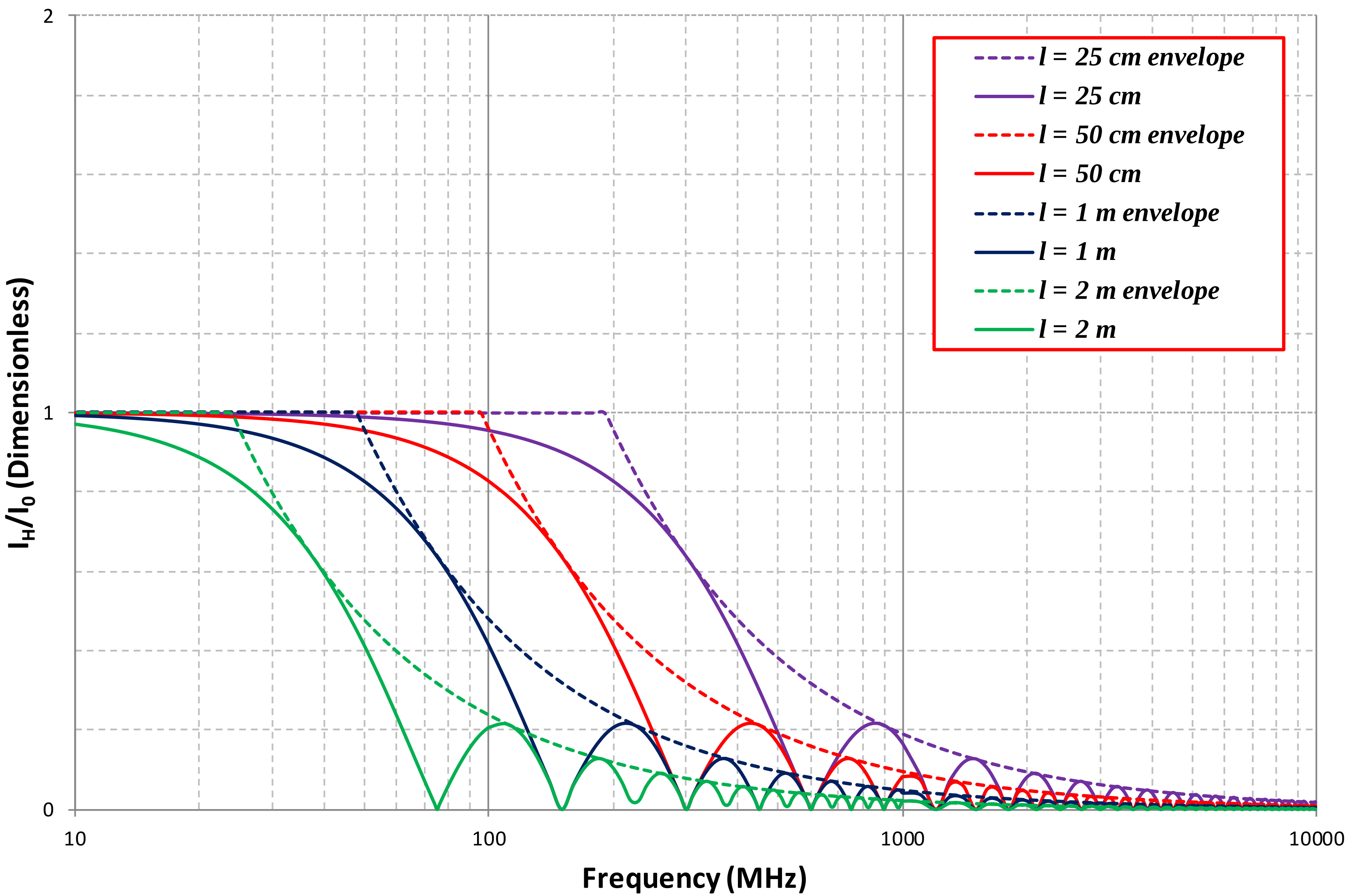
$$dI_d(z)\Delta z = I(z) - I(z + \Delta z)$$

$$dI_d(z) = \frac{I(z) - I(z + \Delta z)}{\Delta z} = \frac{dI(z)}{dz} = -\beta I_0 \sin\beta z$$

$$I_V = -\beta I_0 \int_0^l \sin\beta z dz = I_0 \cos\beta z\Big|_0^l = I_0(\cos\beta l - 1)$$

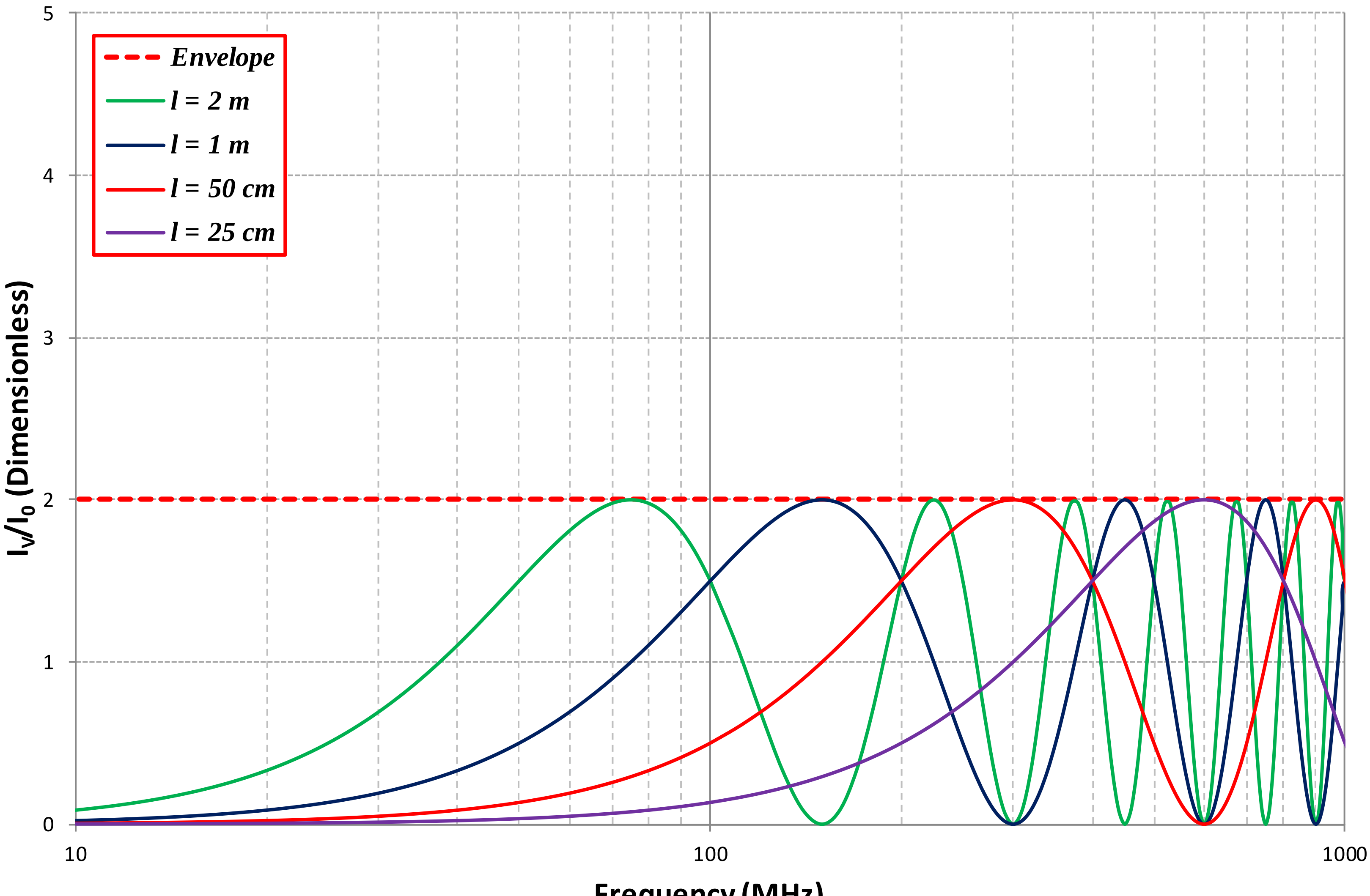
$$\left|\frac{I_V}{I_0}\right|_{ENV} = 2$$

Horizontal (Wire) Current



To b

Vertical (Displacement) Current



Response and Envelope of sin(x)/x

Response of |sin(x)/x|:

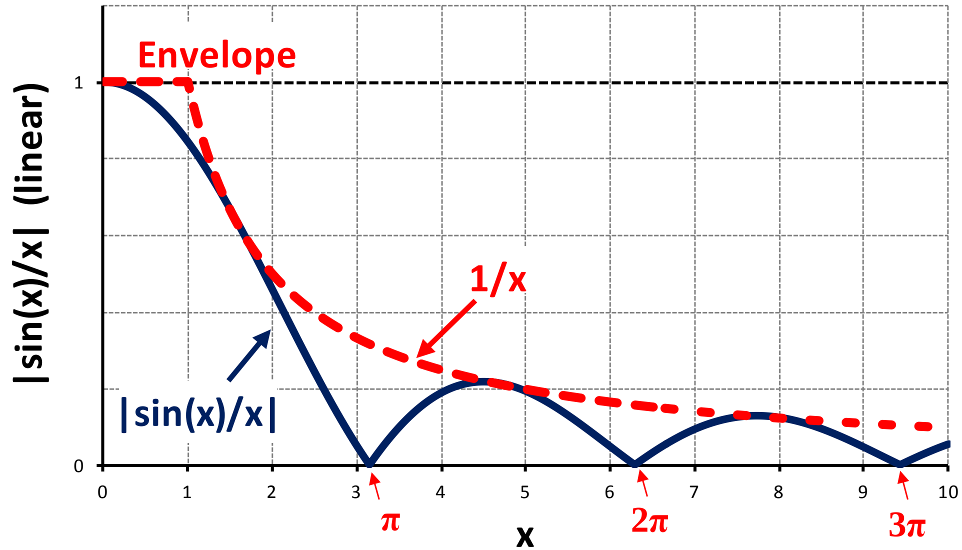
0 for $x = n\pi$

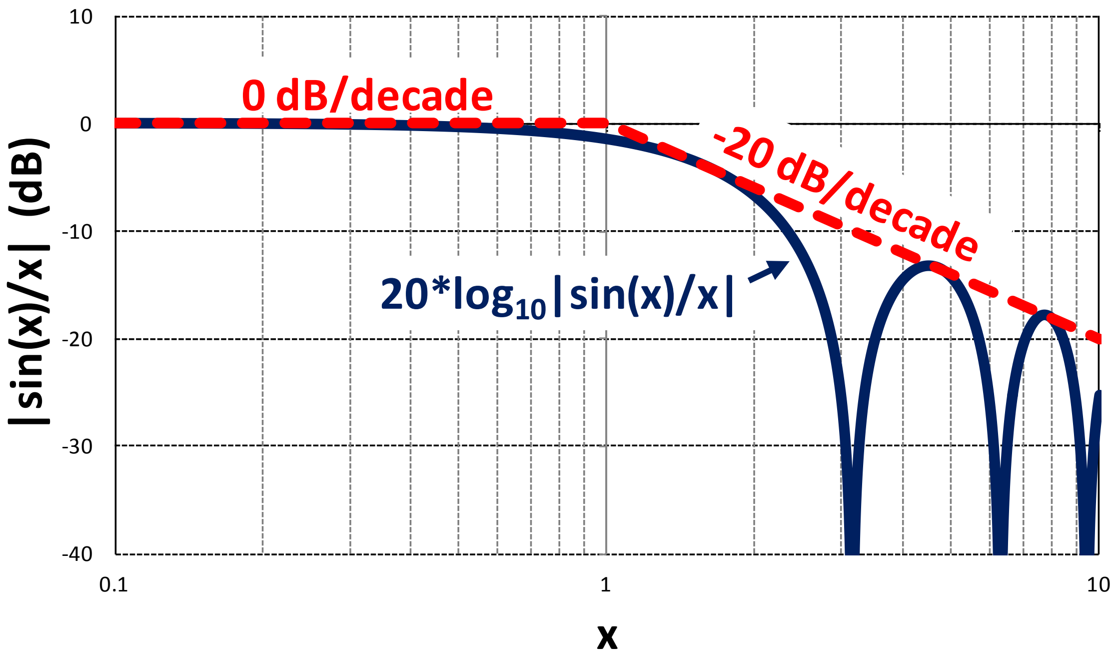
1/x for $x = (n+1)\pi/2$

Envelope of |sin(x)/x|:

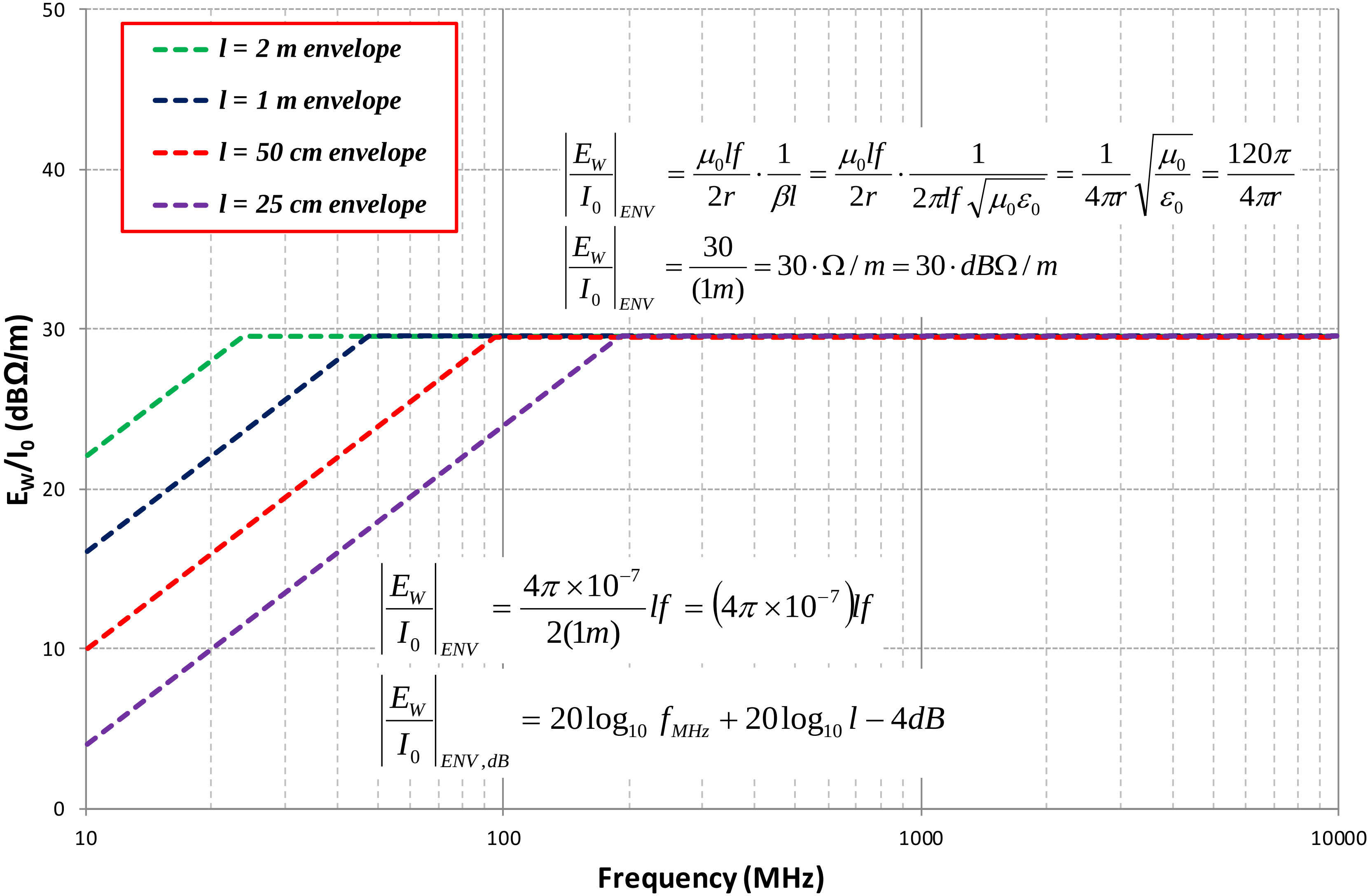
1 for $x \leq 1$

1/x for $x \geq 1$





Horizontal E-Field (No Ground Plane Attenuation)



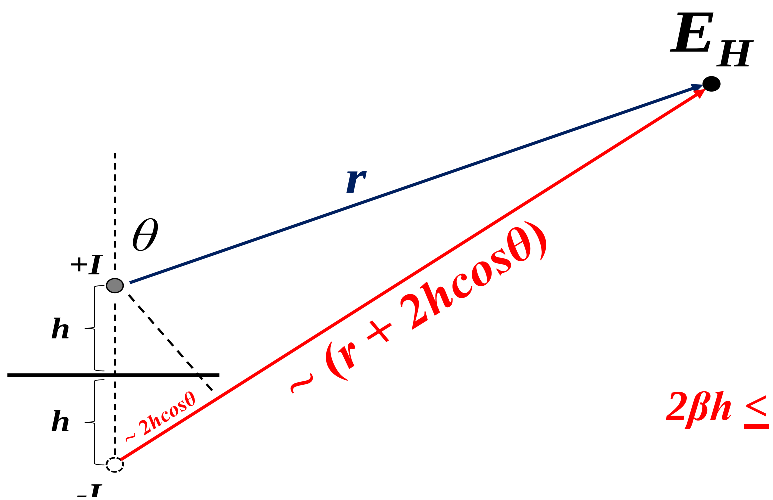
$$\left|\frac{E_W}{I_0}\right|_{ENV} = \frac{\mu_0 l f}{2r}\cdot\frac{1}{\beta l} = \frac{\mu_0 l f}{2r}\cdot\frac{1}{2\pi l f\sqrt{\mu_0\varepsilon_0}} = \frac{1}{4\pi r}\sqrt{\frac{\mu_0}{\varepsilon_0}} = \frac{120\pi}{4\pi r}$$

$$\left|\frac{E_W}{I_0}\right|_{ENV} = \frac{30}{(1m)} = 30\cdot\Omega/m = 30\cdot dB\Omega/m$$

$$\left|\frac{E_W}{I_0}\right|_{ENV} = \frac{4\pi\times10^{-7}}{2(1m)} l f = \left(4\pi\times10^{-7}\right) l f$$

$$\left|\frac{E_W}{I_0}\right|_{ENV,dB} = 20\log_{10} f_{MHz} + 20\log_{10} l - 4dB$$

Ground Plane Attenuation Horizontal Polarization Only)



$$E_H = \frac{\mu_0 lf}{2r} I_H e^{-j\beta r} - \frac{\mu_0 lf}{2(r + 2h\cos\theta)} I_H e^{-j\beta(r+2h\cos\theta)}$$

$$E_H = E_W \left[e^{-j\beta r} - \left(\frac{r}{r + 2h\cos\theta} \right) e^{-j\beta(r+2h\cos\theta)} \right]$$

$$\left| \frac{E_H}{E_W} \right| = \left| \cos\beta r - \frac{r}{(r+2h)} \cos[\beta(r+2h)] \right|$$

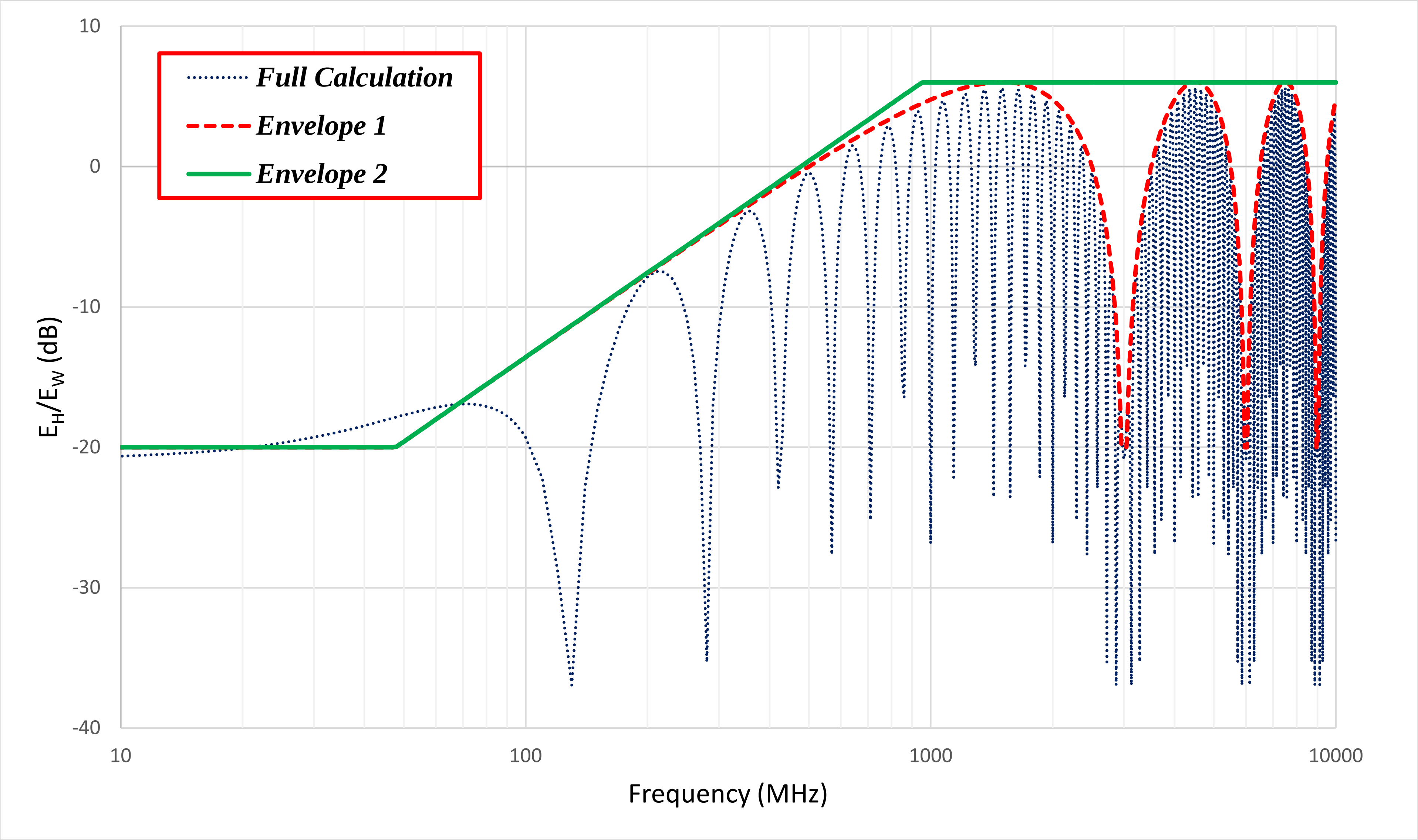
$2\beta h \leq 1$: $$\left| \frac{E_H}{E_W} \right|_{ENV} \approx 1 - \frac{r}{(r+2h)} = \frac{2h}{(r+2h)} \approx 0.1 \approx -20dB$$

$2\beta h \geq 1$: $$\left| \frac{E_H}{E_W} \right| \approx \left| \cos\beta r - \cos[\beta(r+2h)] \right|$$

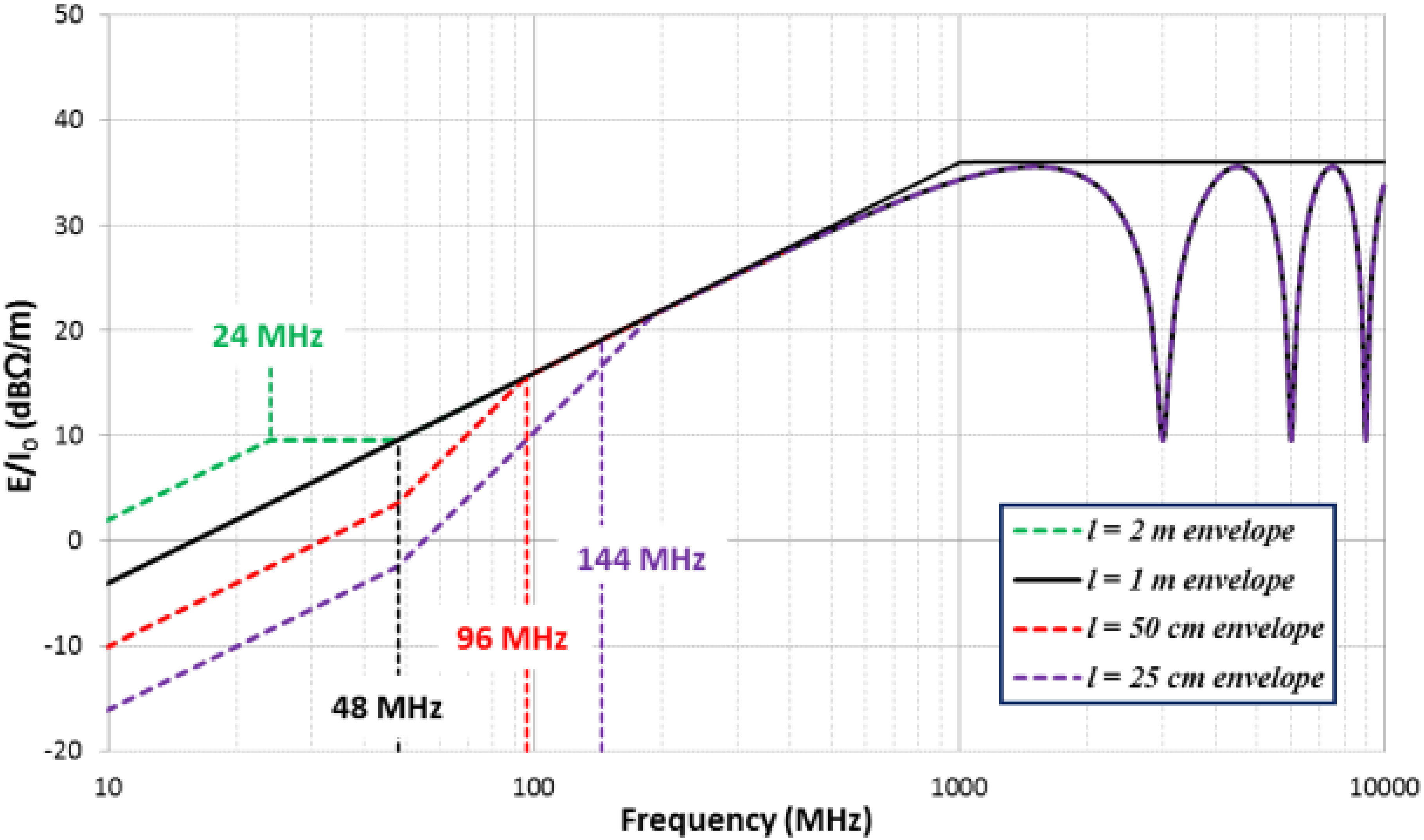
$$\cos A - \cos B = -2\sin\left(\tfrac{A+B}{2}\right)\sin\left(\tfrac{A-B}{2}\right) \rightarrow \left| \frac{E_H}{E_W} \right| \approx \left| 2\sin[\beta(r+h)]\sin(\beta h) \right|$$

$$\left| \frac{E_H}{E_W} \right|_{ENV} \approx \left| 2\sin(\beta h) \right|$$

Ground Plane Attenuation (Gain, Really)

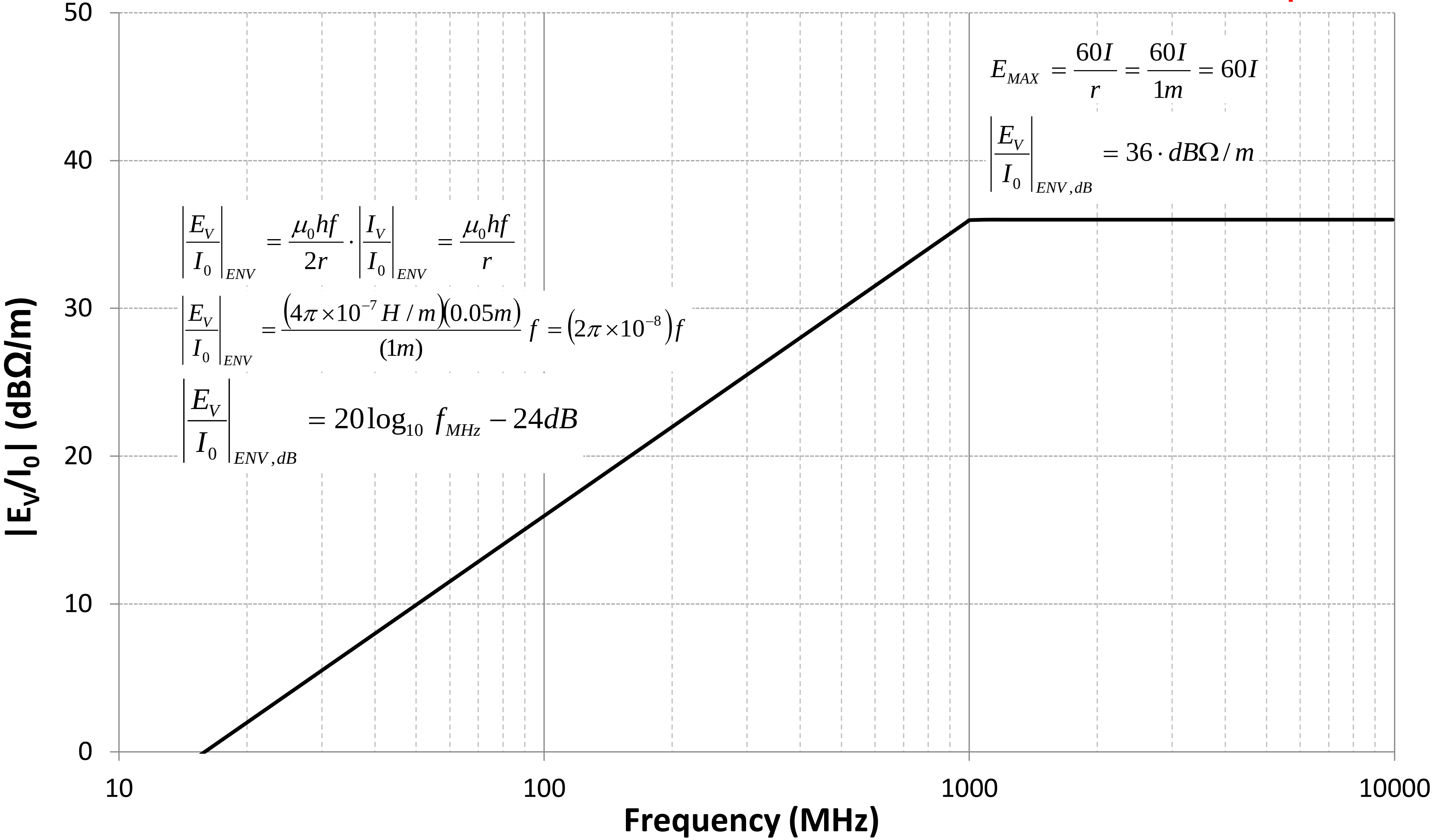


$|E_H/I_0|$ with Ground Plane Attenuation

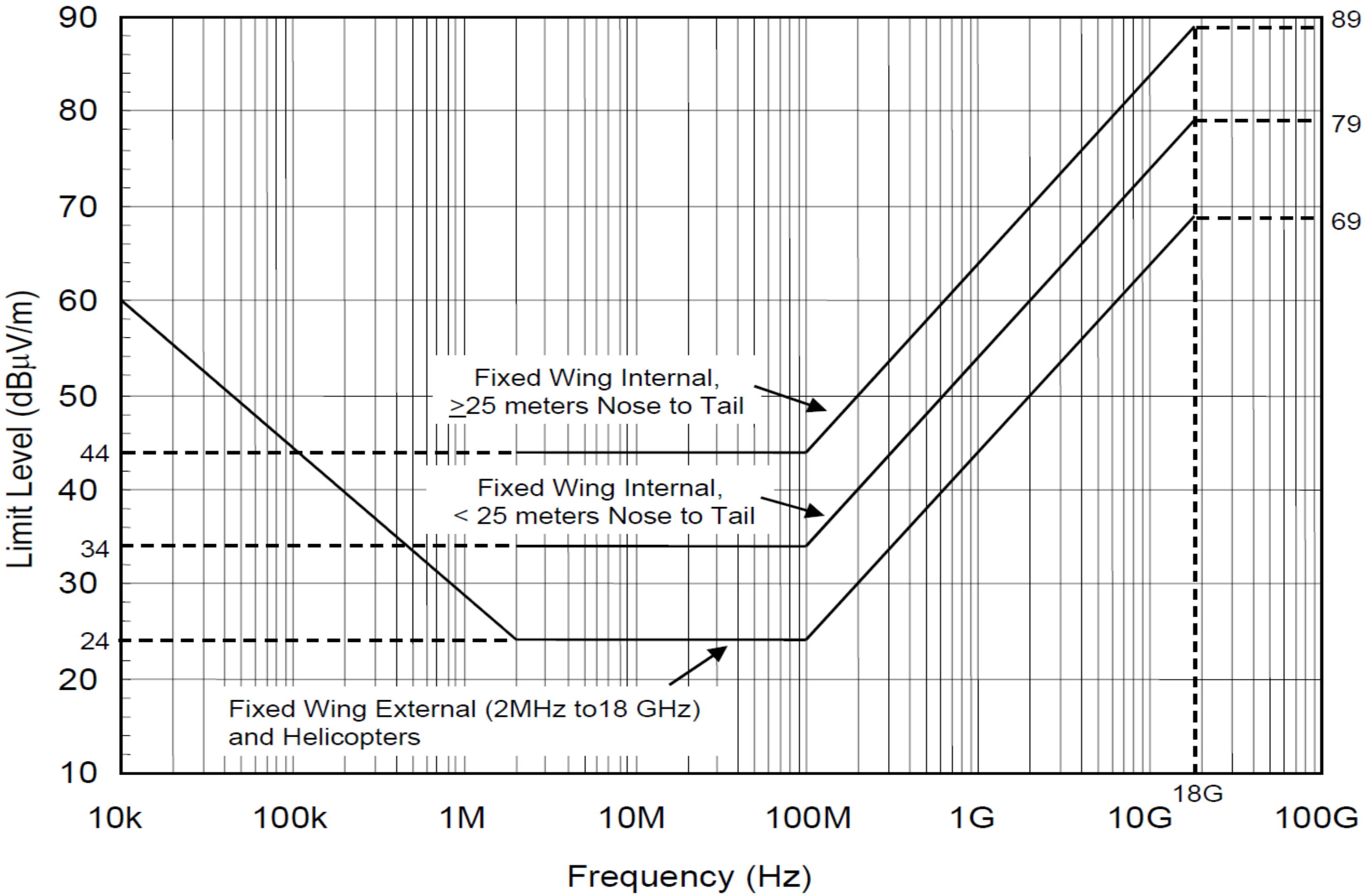


Vertical: $|E_V/I_0|$

Electric field from tuned dipole:



MIL-STD-461 RE102 Limits



Equivalent CMCE Limits