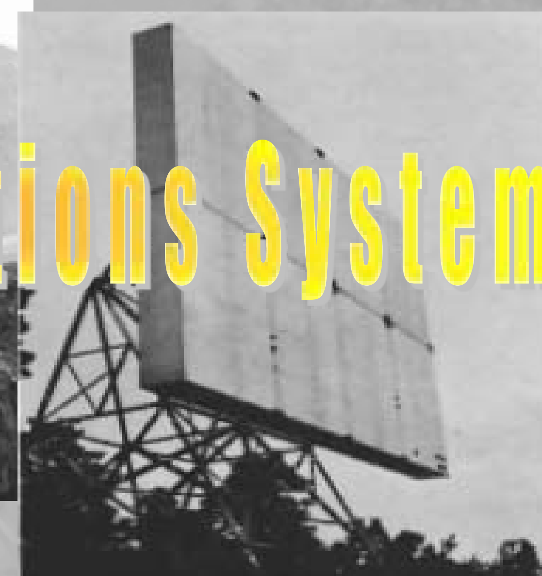
Passive Repeaters

Passive Repeaters



For Rural ITS Communications Systems

Ken Beals
Caltrans District 2
Office of ITS Engineering and Support

Microwave Passive Repeater (Reflector) Design

- The Concept
  - History
  - Identification of Locations
  - Google Earth
  - Visual Sighting
- Design Calculations
  - Manual Calculation
  - Excel Spreadsheet
  - Design Software

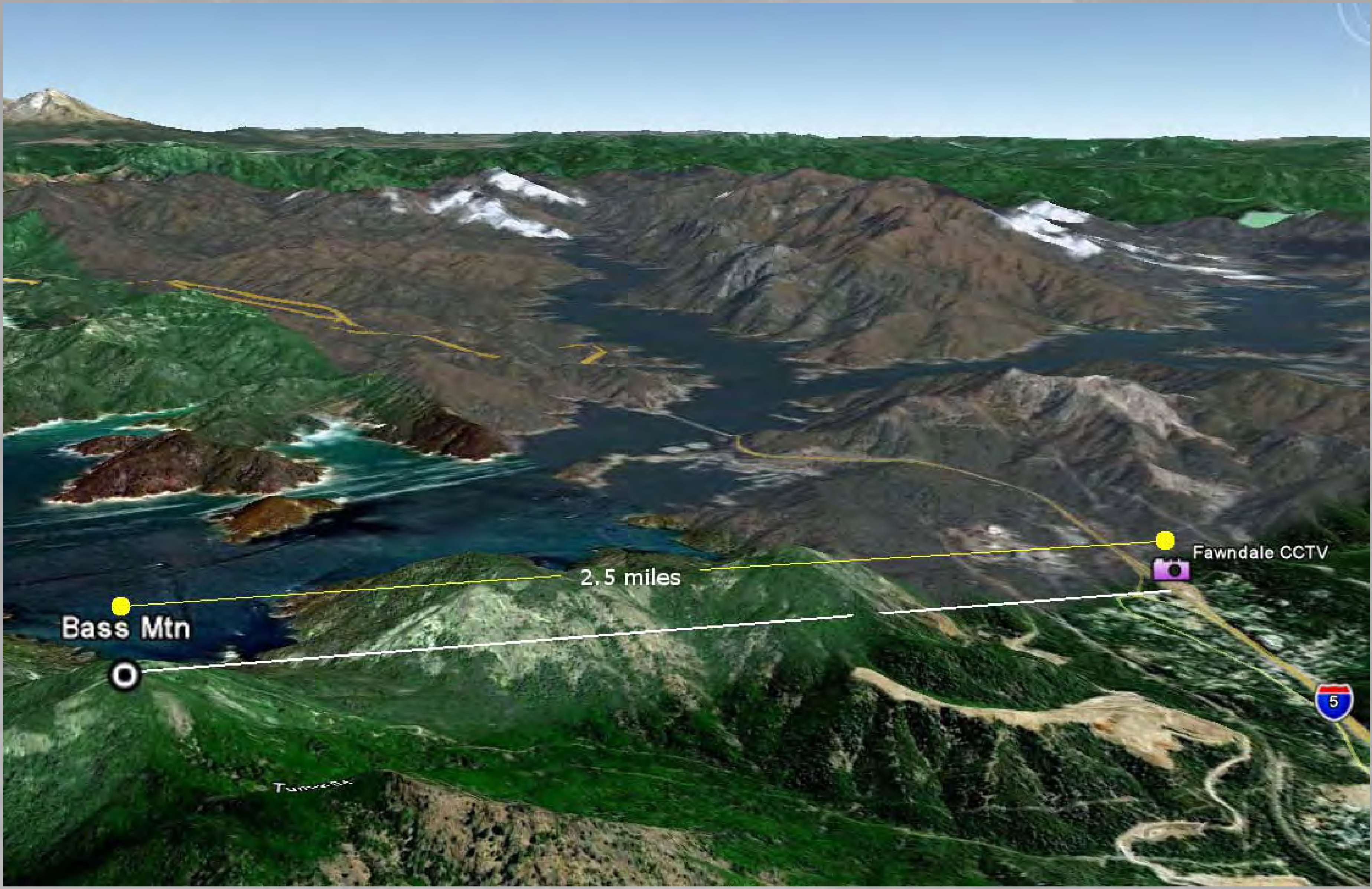
Microwave Passive Repeater (Reflector) Design

- Design
    - Foundation
    - Plans
- Construction
- Adjustment
- Results
- Summary
- Thank You
- Questions and Comments

Passive Repeater History

- Microflect Company started passive repeater installations in 1956
- First used in analog telephone systems
- Especially useful in rugged inaccessible terrain
  - No power or maintenance necessary
  - Can be delivered and installed by helicopter
  - More efficient than back to back parabolic dish antennas
  - No additional frequency channels needed

Google Earth: Direct Path



Google Earth: Reflected Path

Google Earth: Reflector Location

Visual Sighting: What do I look for?

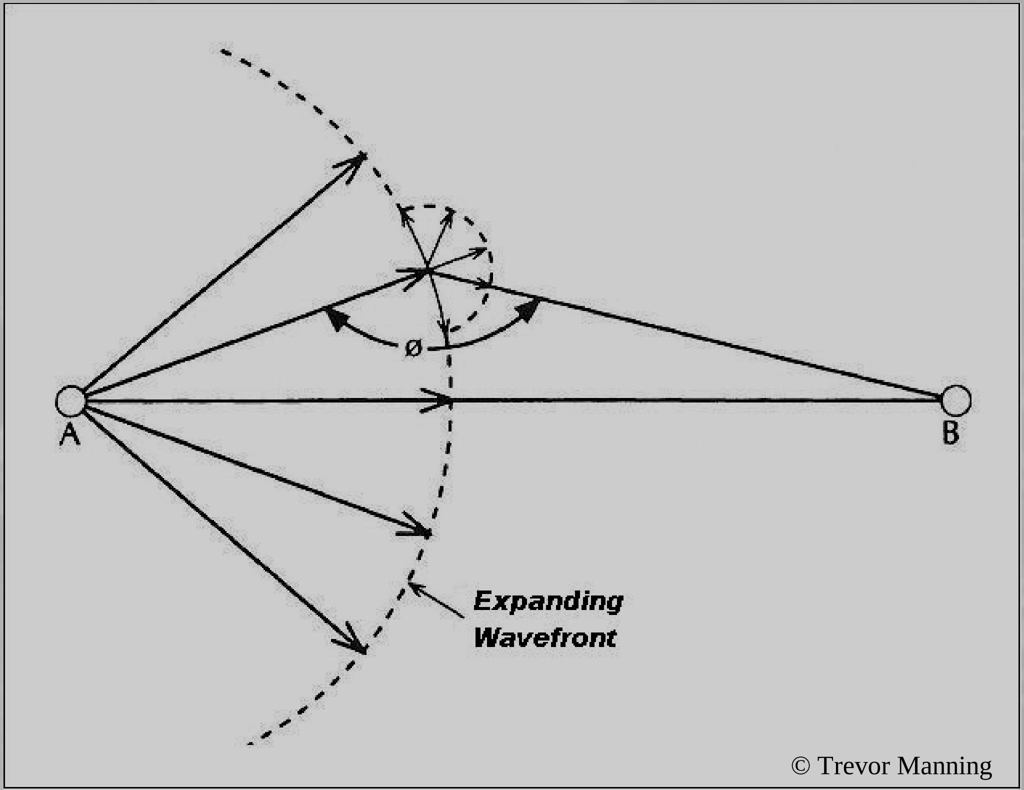
- Visual Sighting
  - Simulation programs only show ground terrain.
  - Need to look for obstructions
    - Vegetation
    - Buildings
    - Possible traffic obstructions

- Fresnel Zone
  - Volume surrounding line of sight path between antennas.
  - Need to keep all obstructions out of the Fresnel zone.

Visual Sighting: Fresnel Zone

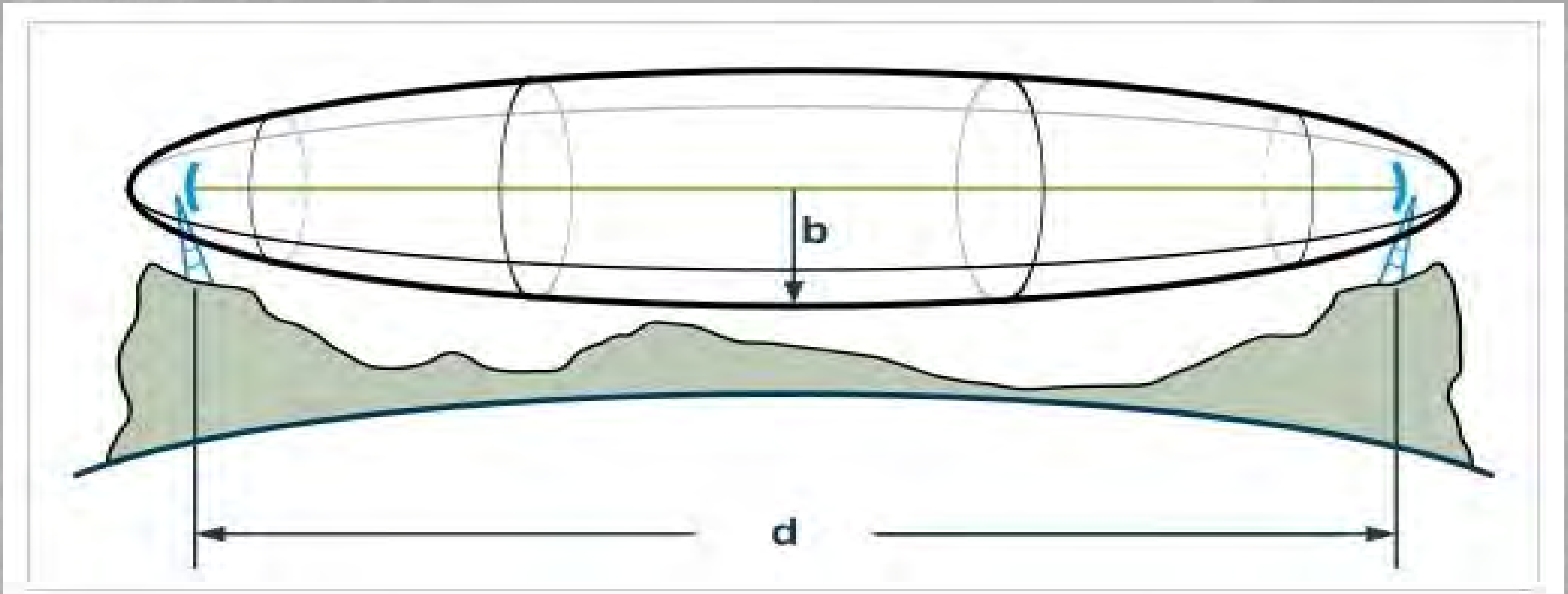
- Fresnel Zone is a volume defined between the receive and transmit antennas.

  - EM waves "spread out" from the transmit antenna (Huygens Principle).
  - If some of the waves are blocked, the received signal will be reduced.



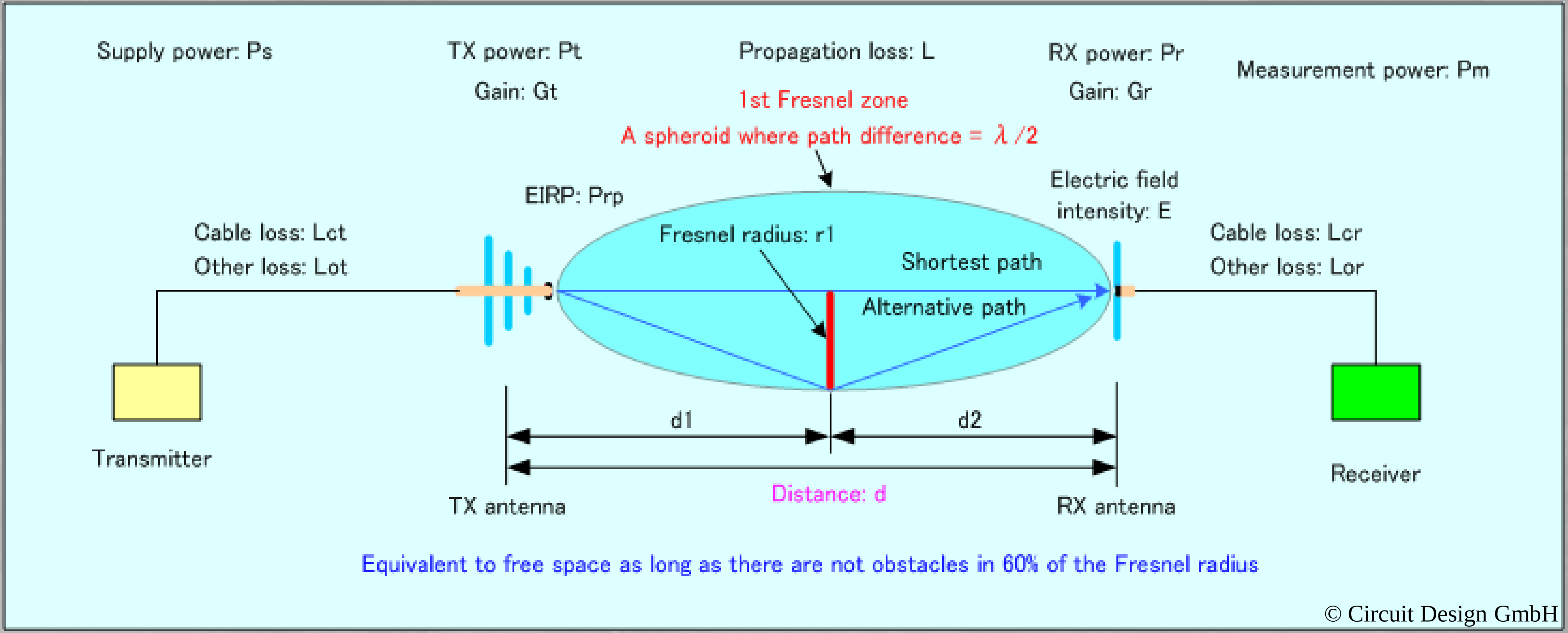
Visual Sighting: Fresnel Zone

- Additional signals can be caused by reflection and refraction off of objects in the path, and can add destructively at the receiver and reduce signal strength. Reflected signals undergo a 180° phase shift.
    - Shape of the volume is an ellipsoid, since the sum of the distance between any point on the ellipsoid and both antennas (located at the foci of the ellipsoid) is a constant.



Visual Sighting: Fresnel Zone

- Size of the Fresnel zone is defined by the wavelength.
  - Each zone is defined by a path that is $\lambda/2$ different in path length.
    - Any obstruction in the Fresnel zone may cause an additional signal to be received via the alternate path. The signal may be in or out of phase: Out of phase signals will reduce signal level.
  - Although multiple Fresnel zones can be defined, only the first zone is significant.



Visual Sighting: Fresnel Zone

- The first Fresnel zone radius may be calculated using:

$$r_{1ft} = 72.05 \times \sqrt{\frac{dist_{mi}}{4 \times freq_{GHz}}}$$

- There are two paths we need to look at:

  - Reflector → Bass Mtn., Dist = 2.3 miles

$$r_{1ft} = 72.05 \times \sqrt{\frac{2.3}{4 \times 6.0}} = 22.3\,ft$$

  - Reflector → Fawndale, Dist = 0.8 miles

$$r_{1ft} = 72.05 \times \sqrt{\frac{0.8}{4 \times 6.0}} = 13.2\,ft$$

Visual Sighting: Fresnel Zone

- The recommended clearance is 60% of the first Fresnel zone.
  - The diameter of the clearance zone will therefore be 60% of two times the recommended clearance radius.
  - For the Bass Mtn. → reflector path:

$$Clearance\ diameter = 2 \times 0.6 \times 22.3 = 26.8\,ft$$

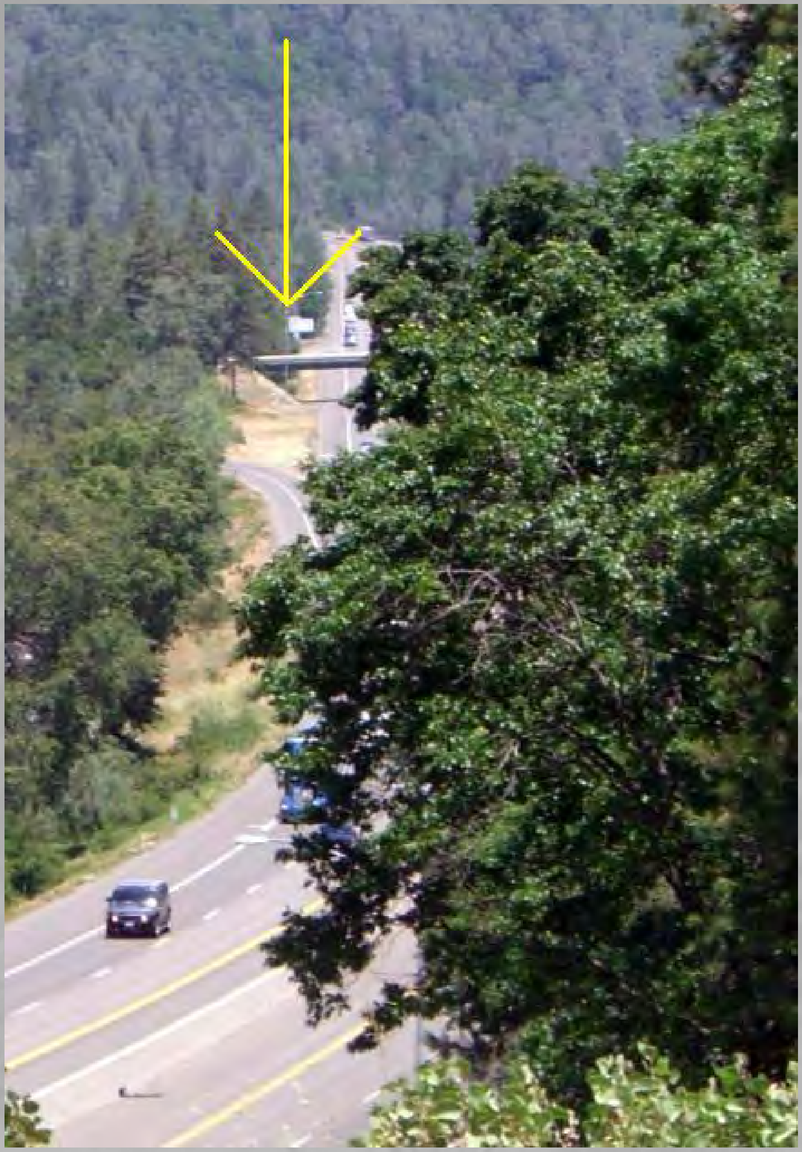
  - For the reflector → Fawndale path:

$$Clearance\ diameter = 2 \times 0.6 \times 13.2 = 15.8\,ft$$

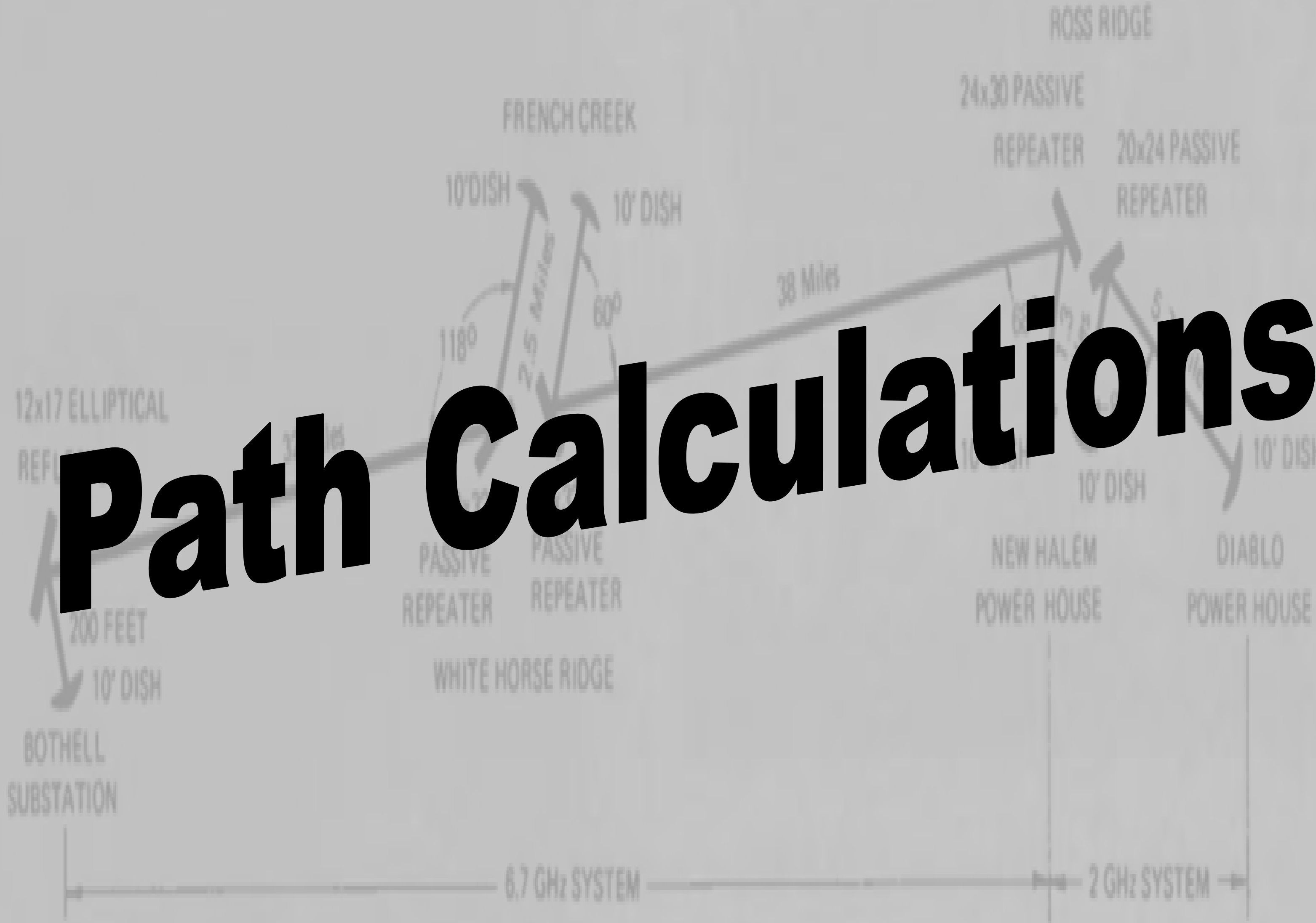
  - For each path, visualize a "tube" with the calculated diameter suspended in space between the endpoints. This is a conservative view, since the ellipsoid is actually narrower at the ends. The calculated value is the clearance at the midpoint of the path.
  - In the case of vegetation, it grows: add additional clearance to keep the path open for a minimum of 5 years.

Fresnel Zone Clearance: Reflector → Bass Mtn.

Fresnel Zone Clearance: Reflector → Fawndale



Path Calculations



Path Calculations: Preliminaries

- ***Warning:*** **Equation Overload Ahead**
  - There are many details to be considered. Although we will look at some shortcuts later, the calculation details are initially presented in long form. (Pop quiz is optional.......)

  - Some symbols and abbreviations that will be used:

    dB = decibel

    dBm = decibel, referenced to 1 milliwatt

    λ = wavelength of a radio signal in meters

    GHz = $1\text{x}10^9$ Hertz (unit of frequency)

    $\log_{10}(X)$ = Logarithm, base 10, of X

  - Distances and elevations will be calculated in miles and feet. Some formulas may need modification if different units are used.
  - The terms “Passive Repeater” and “Reflector” are equivalent and interchangeable.

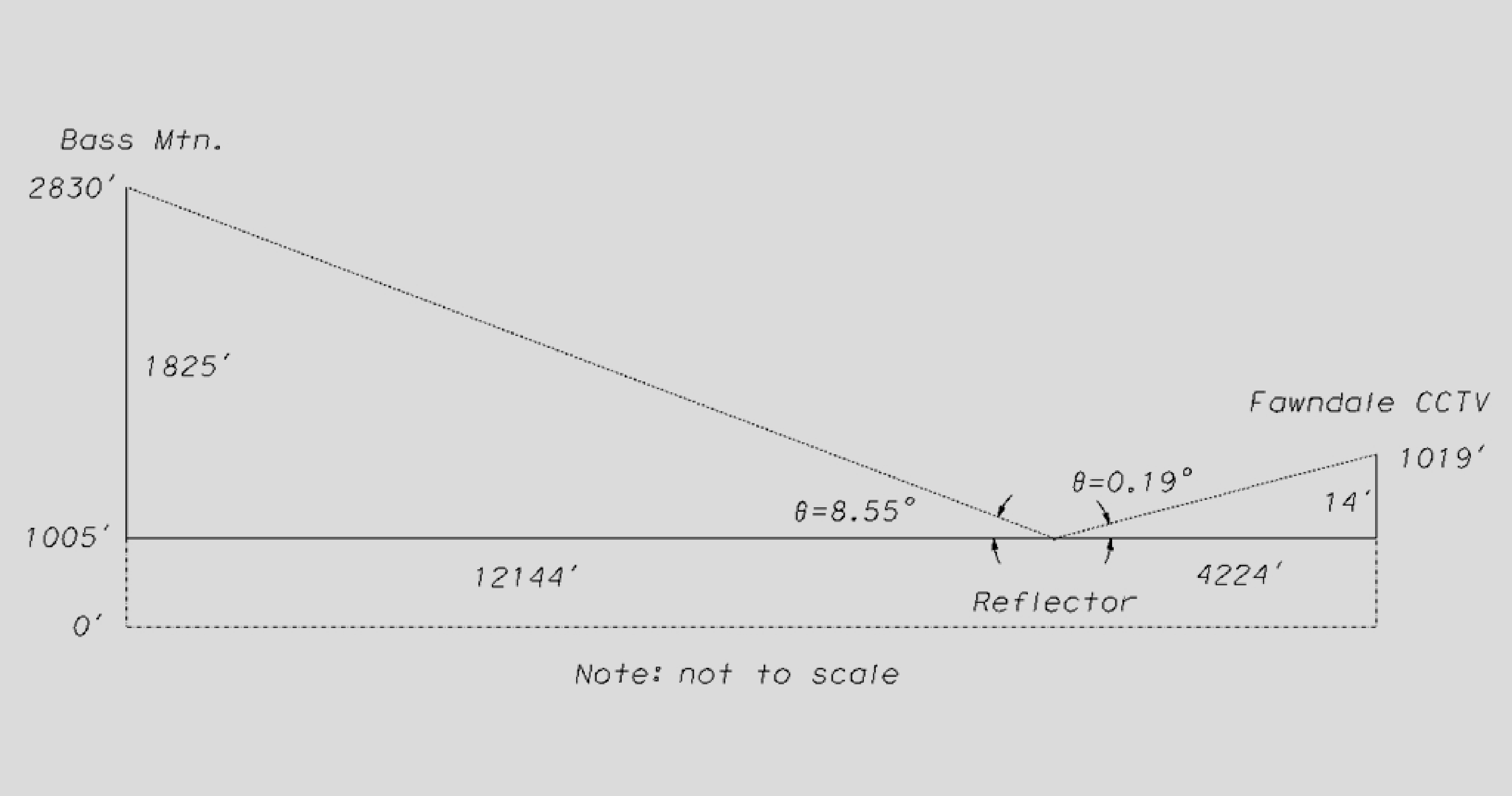
Path Calculations: Preliminaries

- What do I need to know before beginning?
  - Where each location is located in 3D space:
  - Latitude, Longitude, Elevation.
    - **Accuracy is critical.**
      - Handheld GPS is not “close enough” (especially for elevation).
      - Use a professional surveying team.
        - Easily within ± 1 foot elevation, < 1 foot surface accuracy.
- From that information calculate:
  - Distance between points (accurate to 1 foot)
  - Elevation differences between points (accurate to 1 foot)
  - Horizontal angle between paths (two decimal places)
  - Vertical angles between reflector and end points (two decimal places)
    - Correction for earth curvature can be calculated from:

$$Elevation\ Correction_{ft} = \frac{Dist_{mi}^2}{1.5}$$

Path Calculations: Vertical Angles

All elevations are to centerline of antenna/reflector



Path Calculations: Vertical Angles

- Earth curvature correction factors:
  - For the Reflector → Bass Mtn. path:

$$Correction_{ft} = \frac{2.3^2}{1.5} = 3.5\,ft$$

$$Corrected\,Vertical\ Angle = \tan^{-1}\left[\frac{1825.0 - 3.5}{12144.0}\right] = 8.53^\circ$$

  - The difference is 8.55 - 8.53 = 0.02°
  - For the Reflector → Fawndale path:

$$Correction_{ft} = \frac{0.8^2}{1.5} = 0.4\,ft$$

$$Corrected\,Vertical\ Angle = \tan^{-1}\left[\frac{14.0 - 0.4}{4224.0}\right] = 0.18^\circ$$

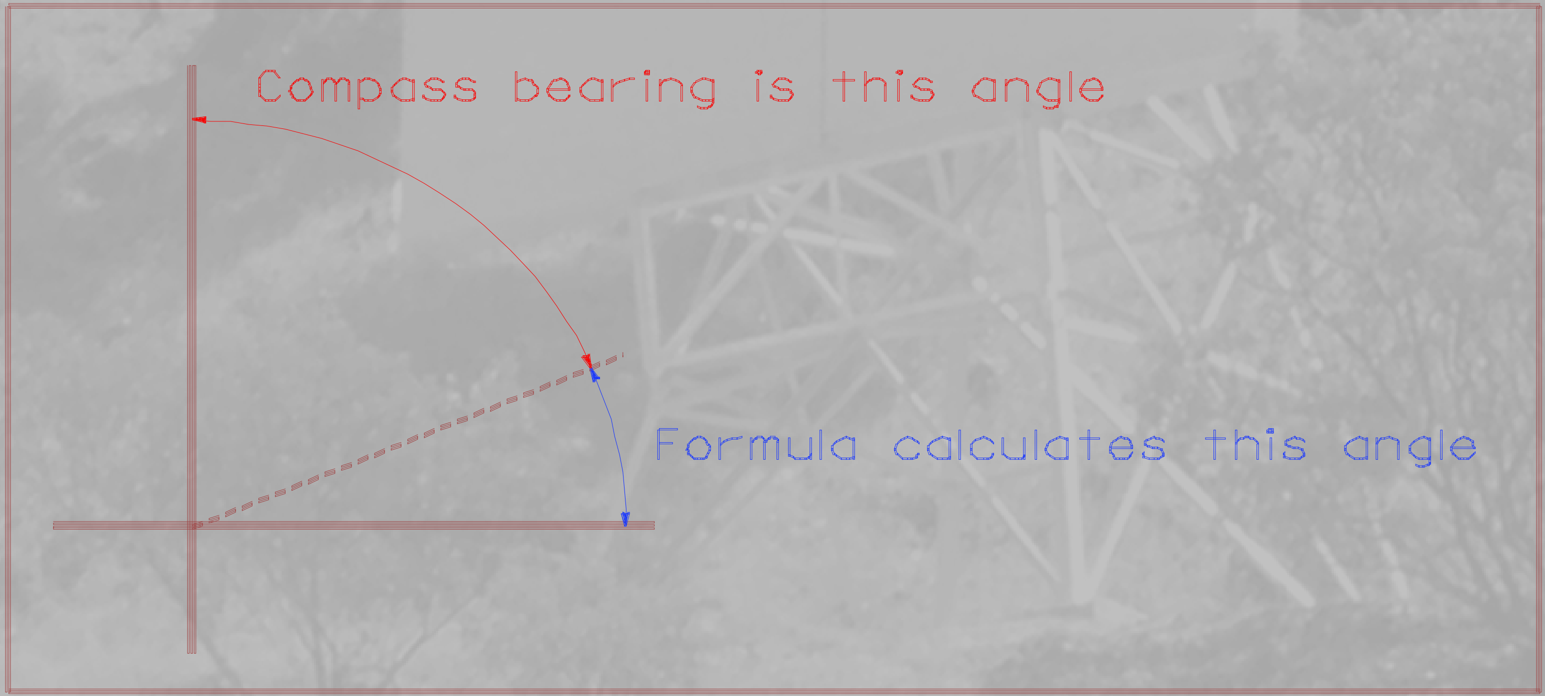
  - The difference is 0.19 – 0.18 = 0.01°

Path Calculations: Horizontal Angle

- Find the bearing from the reflector to each end:

$$\theta = \tan^{-1}\left[\frac{\cos(Lat_1)\times\sin(Lat_2) - \sin(Lat_1)\times\cos(Lat_2)\times\cos(\Delta Long)}{\sin(\Delta Long)\times\cos(Lat_2)}\right]$$

- Note: This formula calculates an angle from the 'x' axis in the Cartesian coordinate system. Compass bearings are referenced from North = 0°, so we will need to convert the angle to a compass bearing.



Path Calculations: Horizontal Angle

- For the reflector to Bass Mtn. path:

$$\theta = \tan^{-1}\left[\frac{\cos(40.7208^\circ)\times\sin(40.7328^\circ)-\sin(40.7208^\circ)\times\cos(40.7328^\circ)\times\cos(-0.0404^\circ)}{\sin(-0.0404^\circ)\times\cos(40.7328^\circ)}\right] = -21.42^\circ$$

  - Correcting for the change of axis:

$$Compass\ \ Bearing = 90.00^\circ - (-21.42^\circ) = 111.42^\circ$$

- For the reflector to Fawndale path:

$$\theta = \tan^{-1}\left[\frac{\cos(40.7208^\circ)\times\sin(40.7308^\circ)-\sin(40.7208^\circ)\times\cos(40.7308^\circ)\times\cos(0.0063^\circ)}{\sin(0.0063^\circ)\times\cos(40.7308^\circ)}\right] = 64.48^\circ$$

  - Correcting for the change of axis:

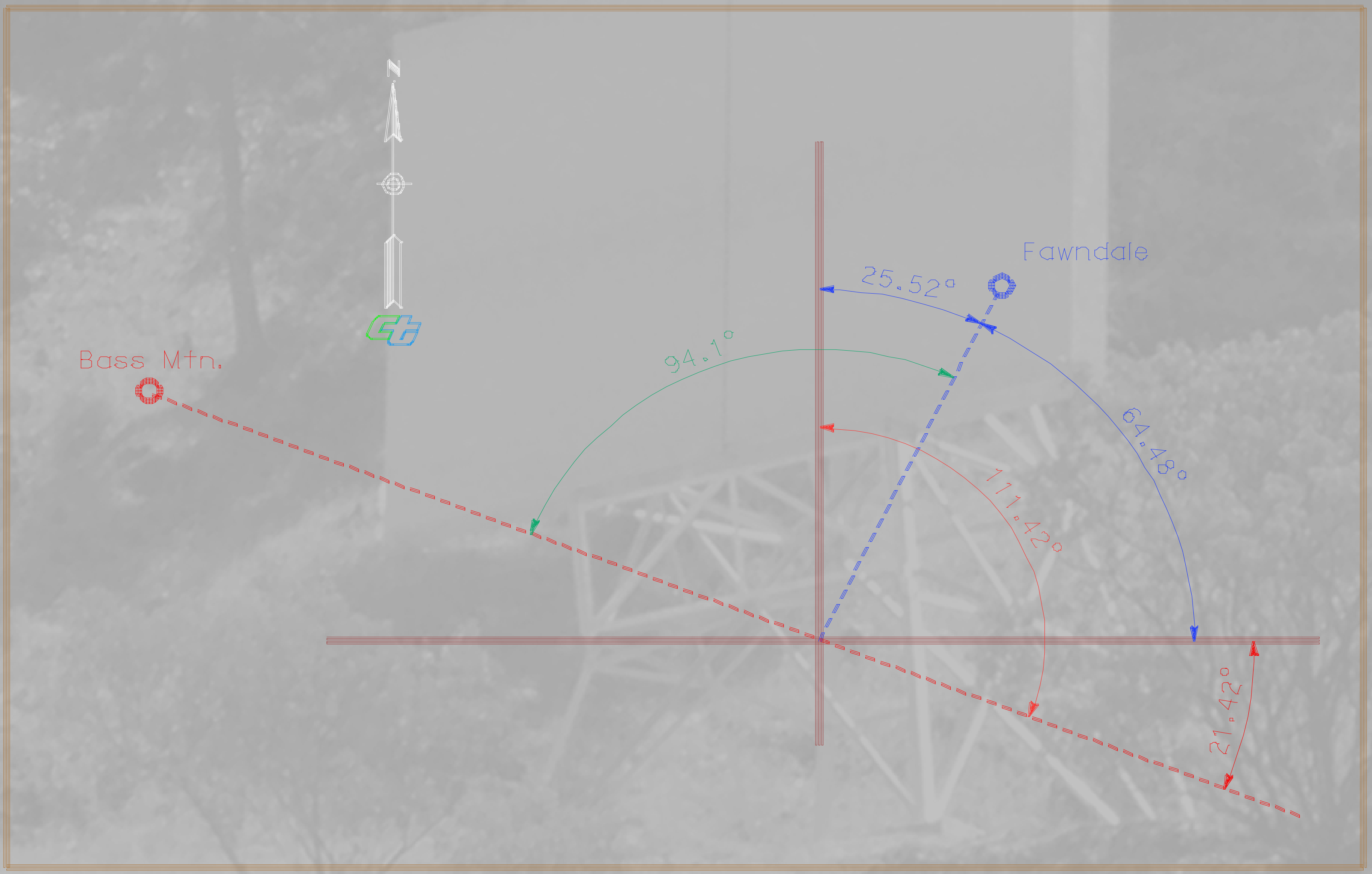
$$Compass\ \ Bearing = 90.0^\circ - 64.48^\circ = 25.52^\circ$$

  - The horizontal angle between the paths is:

$$360^\circ - (111.42^\circ + 180^\circ) + 25.52^\circ = 94.10^\circ$$

Path Calculations: Horizontal Angle

- Let's see what this looks like:




Fade Margin

Path Calculations: Fade Margin

- Fade margin is the "extra" signal strength required at the receiver to allow for atmospheric and other conditions that cause variation in the received signal level.
  - Several models are available for calculating fade margin. This model is known as the "Lenkurt" model, and tends to give the most conservative values.

$$FM = -10\log_{10}\left[\frac{1-availability}{TF \times CF \times 10^{-5} \times \dfrac{Freq}{4} \times Dist^{3}}\right]$$

Availability: relative uptime in the range of 0 – 1.0 (100% uptime = 1.0)

TF = Terrain factor

CF = Climate factor

Freq = Frequency in GHz

Dist = Total path distance end to end in miles

Path Calculations: Availability

RELIABILITY %	OUTAGE TIME %	OUTAGE TIME PER		
		YEAR	MONTH (Avg.)	DAY (Avg.)
0	100	8760 hours	720 hours	24 hours
50	50	4380 hours	360 hours	12 hours
80	20	1752 hours	144 hours	4.8 hours
90	10	876 hours	72 hours	2.4 hours
95	5	438 hours	36 hours	1.2 hours
98	2	175 hours	14 hours	29 minutes
99	1	88 hours	7 hours	14.4 minutes
99.9	0.1	8.8 hours	43 minutes	1.44 minutes
99.99	0.01	53 minutes	4.3 minutes	8.6 seconds
99.999	0.001	5.3 minutes	26 seconds	0.86 seconds
99.9999	0.0001	32 seconds	2.6 seconds	0.086 seconds

Path Calculations: Terrain/Climate Factor

Factors were determined emperically. Most of these models were developed in the 1960s and 1970s.

		Mountainous, dry	Normal, interior	hot, humid
	climate factor (b)	1/8	1/4	1/2
terrain factor (a)				
rough/dry	0.25	99.999923	99.999846	99.999691
	0.5	99.999846	99.999691	99.999382
	0.75	99.999768	99.999537	99.999074
average	1	99.999691	99.999382	99.998765
	2	99.999382	99.998765	99.997529
	3	99.999074	99.998147	99.996294
smooth (over water)	4	99.998765	99.997529	99.995059

Path Calculations: Fade Margin

• The fade margin formula assumes a single path, where we actually have two paths. The accepted industry standard is to calculate the fade margin over the single longer path.

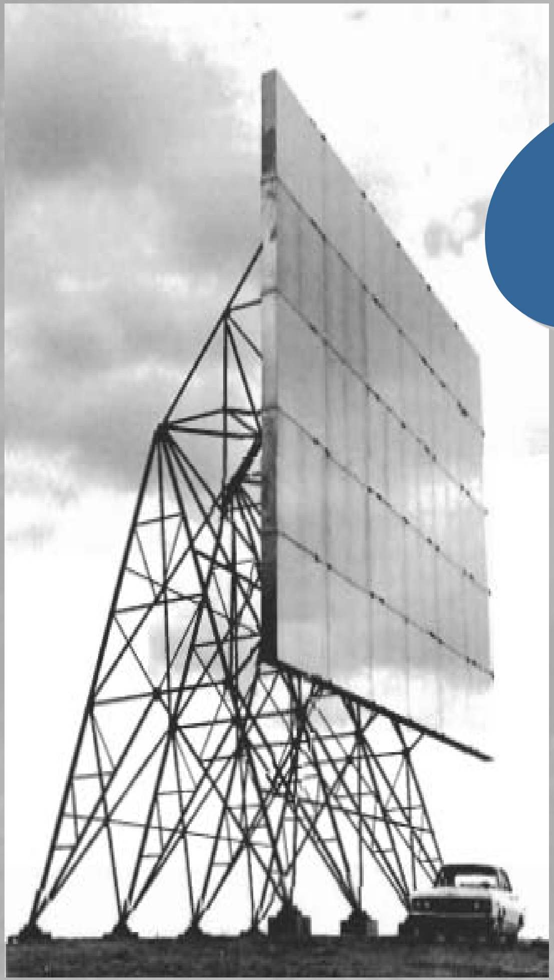
The fade margin for the proposed link is calculated using the following factors:

Availability: 0.99999 (99.999%)
Terrain factor = 1.0 (Average terrain)
Climate factor = 0.250 (Normal interior climate)
Distance = 3.1 miles
Frequency = 6.0 GHz

$$FM = -10\log_{10}\left[\frac{1-0.99999}{1.0\times0.250\times10^{-5}\times\frac{6.0}{4}\times3.1^{3}}\right] = 10.5dB$$

The fade margin is added to the receiver threshold value to determine the required minimum received power level $P_{r.}$

Reflector Size



Path Calculations: Reflector Size

• The required size of the reflector is determined by calculating the required gain of the reflector that will result in the necessary minimum signal at the receiver that was calculated earlier.

The path loss for each path is determing using a version of the Friis equation:

$$PL_{dB} = 96.6 + 20\log_{10}(Freq_{GHz}) + 20\log_{10}(Dist_{Mi})$$

For the Reflector → Bass Mtn. path:

$$PL_1 = 96.6 + 20\log_{10}(6.0) + 20\log_{10}(2.3) = 119.1\ dB$$

For the Reflector → Fawndale path:

$$PL_2 = 96.6 + 20\log_{10}(6.0) + 20\log_{10}(0.8) = 109.9\ dB$$

Path Calculations: Reflector Size

Now determine the required reflector gain:

Standard received power equation:

$$P_r = P_t + G_t - PL_1 - PL_2 + G_r - L_{sys} + G_{ref}$$

Rearrange to solve for the reflector gain:

$$G_{ref} = P_r - P_t - G_t + PL_1 + PL_2 - G_r + L_{sys}$$

Where:

PL_x = Free Space Path Loss
G_x = gain of receive or transmit antenna, or reflector
L_{sys} = System Losses (coax, connectors, etc.)
P_x = Power transmitted (t) or received (r)

note: all values in dB or dBm as appropriate

Path Calculations: Reflector Size

Plug in the numbers:

PL_1 = 119.1 dB
PL_2 = 109.9 dB
G_x = 29.0 dB (Gain of transmit and receive antenna, each)
L_{sys} = 12 dB (System losses (coax, connectors, etc.))
P_t = +10 dBm (Transmitter power)
P_r = -84.5 dBm (Receiver threshold + fade margin)

$$G_{ref} = -84.5 - 10.0 - 29.0 + 119.1 + 109.9 - 29.0 + 12.0 = 88.5\ dB$$

Path Calculations: Reflector Size

PASSIVE REPEATER GAIN, dB
FOR α = 0 @ 100% EFFICIENCY (Except for shaded areas B,C,and D)

(Sizes: Height in Feet X Width in Feet / Dimensions in Meters)

Incremental Gain (dB) → 1.58 4.44 1.58 1.34 3.10 1.58 1.94 2.50 1.02 2.50 1.94 1.58 2.85 1.58

FREQ. (GHz) Center of Band	8x10 / 2.43x3.04	8x12 / 2.43x3.65	10x16 / 3.04 x 4.87	12x16 / 3.65 x 4.87	14x16 / 4.26 x 4.87	16x20 / 4.87 x 6.09	16x24 / 4.87 x 7.31	20x24 / 6.09 x 7.31	20x32 / 6.09 x 9.75	24x30 / 7.31 x 9.14	30x32 / 9.14 x 9.75	30x40 / 9.14 x 12.19	30x48 / 9.14 x 14.63	40x50 / 12.19 x 15.24	40x60 / 12.19 x 18.29
1.780	70.35	71.93	76.37	77.95	79.29	82.39	83.97	85.91	88.41	89.43	91.93	93.87	95.45	98.30	99.88
1.920	71.66	73.24	77.68	79.26	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	93.24	95.18	96.76	99.61	101.19
2.000	72.37	73.95	78.39	79.97	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	93.95	95.89	97.47	100.32	101.90
2.120	73.38	74.96	79.40	80.98	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	94.96	96.90	98.48	101.33	102.91
2.140	73.54	75.12	79.56	81.14	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	95.12	97.06	98.64	101.49	103.07
2.170	73.79	75.37	79.81	81.39	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	95.37	97.31	98.89	101.74	103.32
2.190	73.95	75.53	79.97	81.55	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	95.53	97.47	99.05	101.90	103.48
2.595	76.89	78.47	82.91	84.49	85.83	88.93	90.51	92.45	94.95	[illegible]	98.47	100.41	101.99	104.84	106.42
3.950	84.19	85.77	90.21	91.79	93.13	96.23	97.81	99.75	102.25	103.27	105.77	107.71	109.29	112.14	113.72
4.700	87.21	88.79	93.23	94.81	96.15	99.25	100.83	102.77	105.27	106.29	108.79	110.73	112.31	115.16	116.74
6.175	91.95	93.53	97.97	99.55	100.89	103.99	105.57	107.51	110.01	111.03	113.53	115.47	117.05	118.90	120.48
6.725	93.44	95.02	99.46	101.04	102.38	105.48	107.06	109.00	111.50	112.52	115.02	116.96	118.54	120.39	121.97
7.000	94.13	95.71	100.15	101.73	103.07	106.17	107.75	109.69	112.19	113.21	115.71	117.65	119.23	121.08	122.56
7.435	95.18	96.76	101.20	102.78	104.12	107.22	108.80	110.74	113.24	114.26	116.76	118.70	119.28	122.13	122.71
8.075	96.61	98.19	102.63	104.21	105.55	108.65	110.23	112.17	114.67	115.69	118.19	119.13	120.71	122.56	124.14
11.200	102.30	103.88	108.32	109.90	111.24	114.34	115.92	117.86	119.36	120.38	122.88	123.82	125.40	127.25	128.83
12.450	104.14	105.72	110.16	111.74	113.08	116.18	117.76	119.70	121.20	122.22	123.72	125.66	127.24		
12.825	104.65	106.23	110.67	112.25	113.59	116.69	118.27	119.21	121.71	122.73	124.23	126.17	127.75		
13.075	104.99	106.57	111.01	112.59	113.93	117.03	118.61	119.55	122.05	123.07	124.57	126.51			
14.825	107.17	108.75	113.19	114.77	116.11	119.21	119.79	121.73	123.23	124.25	126.75				

88.79	93.23
93.53	97.97

Question from the gallery....

How can a chunk of aluminum have so much "Gain"........

Reflector Gain

• Gain (in dB) or Directivity (a linear factor) can be determined directly from the effective aperture of an antenna. The aperture is the "capture area" of an antenna. It determines how much of the radiated EM plane wave power is intercepted by the antenna.

• An *isotropic* antenna is one that receives or transmits equally well in all directions (in 3D space). Also known as a *point source.*

The effective aperture of an isotropic antenna is: $\frac{\lambda^2}{4\pi}$

and is considered the "reference" aperture.

Directivity (linear) or Gain (in dB) is defined as the ratio of the antenna aperture (or area) to the isotropic aperture.

$$Directivity = \frac{Aperture}{\frac{\lambda^2}{4\pi}} \qquad Gain_{dB} = 20\log_{10}\left[\frac{Aperture}{\frac{\lambda^2}{4\pi}}\right]$$

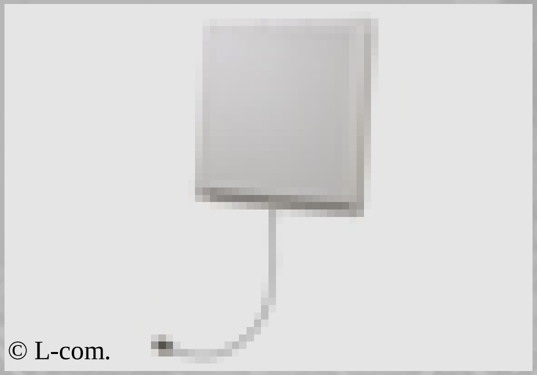
Reflector Gain

- Note that the "gain" of an antenna is completely independent of the physical shape.
  - Antennas that look different can have the same gain:

$$Gain = 8\,dBi$$

$$Length = 1.2m$$
$$Width = 0.040m$$
$$Area = 0.048m^2$$

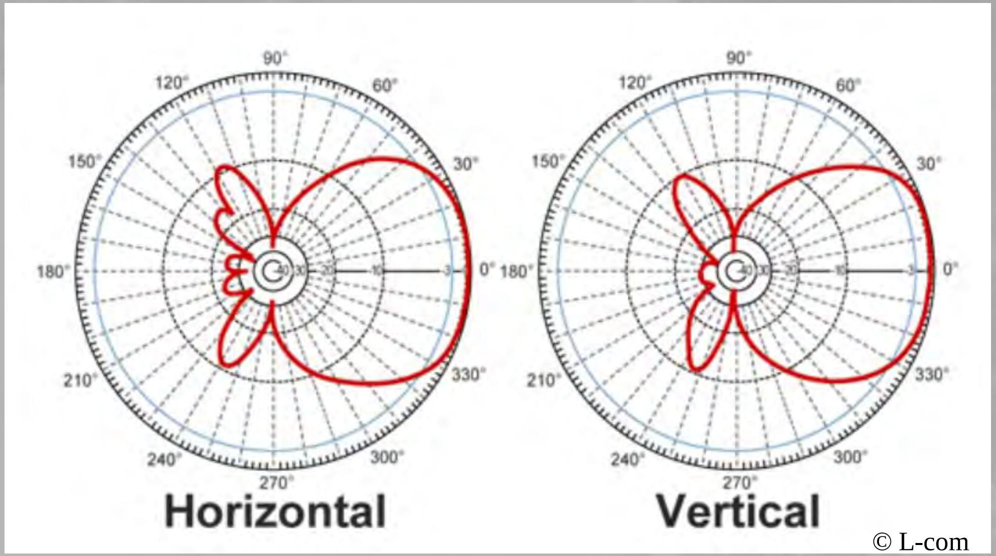
$$Gain = 8\,dBi$$

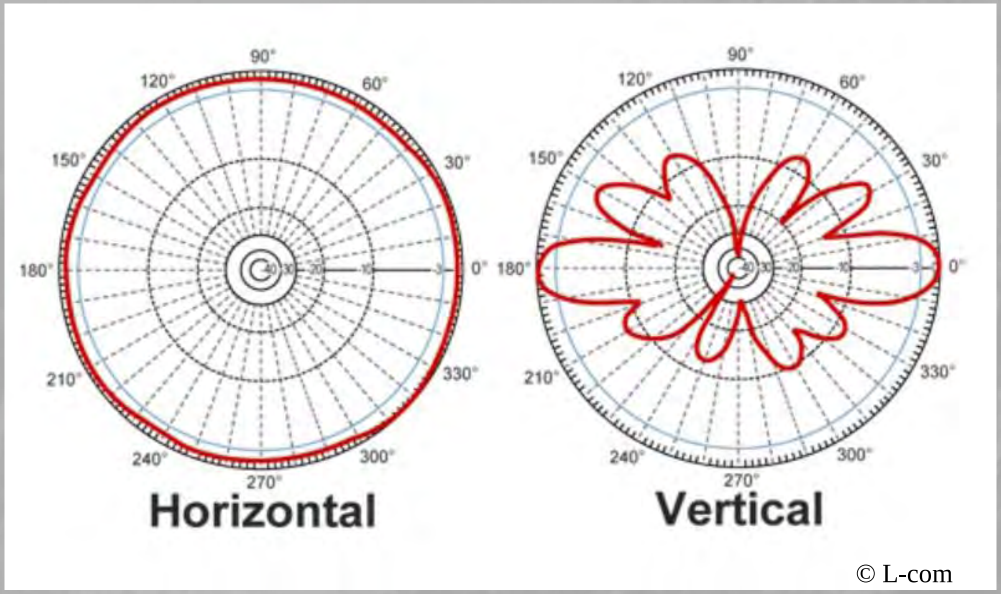


$$Length = 0.216m$$
$$Width = 0.216m$$
$$Area = 0.047m^2$$

Reflector Gain

- Although the "Gain" is equal, the patterns (what directions are favored) are totally different.
  - It is basically the "balloon" principle: squeezing the pattern on one side will make it expand on the other side





Reflector Gain

• For the reflector, gain will be the ratio of the aperture of the reflector (physical area) to the isotropic aperture:

A 16’ x 10’ reflector (4.88 m x 3.05 m) operated at 6.0 GHz has a gain of:

$$G_{ref} = 20\log_{10}\left[\frac{4.88\times 3.05}{\frac{0.05^2}{4\pi}}\right] = 97.5dB$$

Note that this gain is only at the wavelength specified

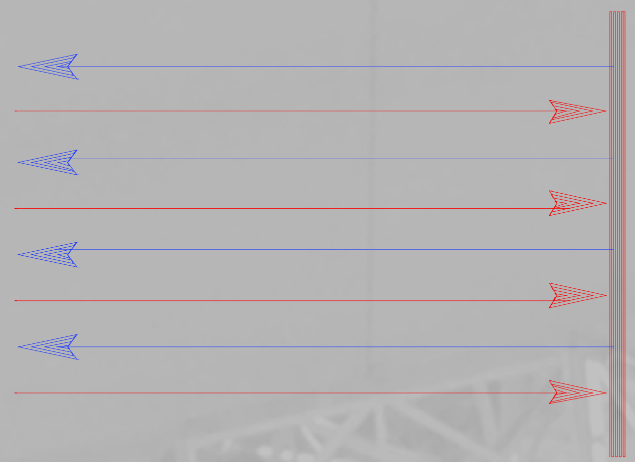
Lower frequencies (larger λ) means lower gain

At 2.4 GHz, the reflector would have to be 40’ x 25’ for the same gain

*It just so happens that this is the reflector size used for this project.

Reflector Gain

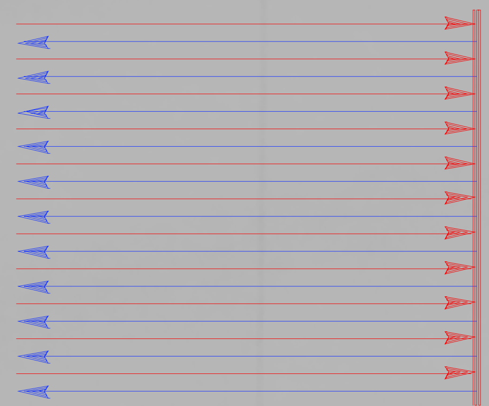
Problem: This is the gain of the reflector with the EM wave normal to the reflector face:



What happens when the waves are not normal to the surface?

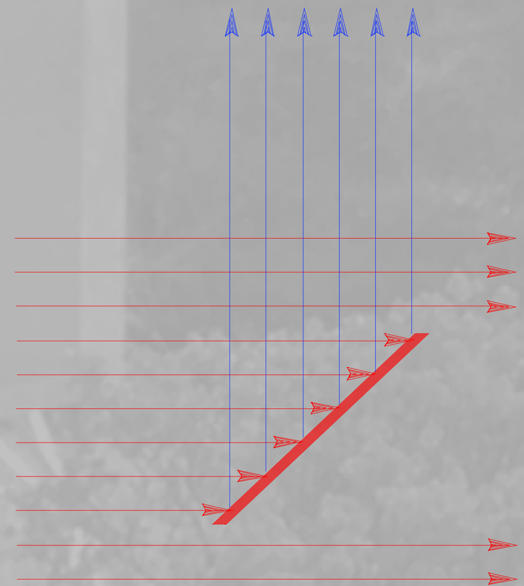
Reflector Gain

Reflector Effective Area: Look at three cases:



Waves normal to the surface:

Effective Area = Reflector area



Waves intersect at an angle to the normal:

Effective area = some fraction of the Reflector area

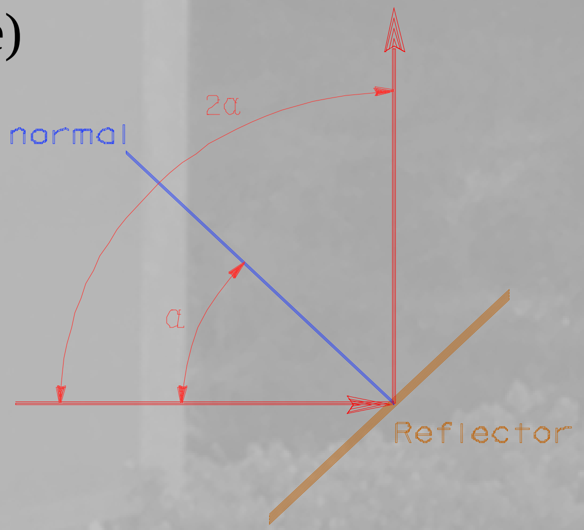
Waves intersect at 90° to the normal:

Effective area = 0

Reflector Gain

The result is what you would expect:

Reflector effective area = Area * cos(wave intercept angle)



By the law of reflection, we know that the angle of the incoming wave and the angle of the outgoing wave are equal with respect to the normal of the surface.

Since we have already calculated the angle between the paths, the intercept angle is simply one-half of the included angle.

The wave intercept angle is given the symbol α, and the included angle is therefore 2α.

For the 16'x10' (4.88 m x 3.05 m) reflector used in this design:

$$A_{effective} = 14.88 \times \cos(47.05°) = 10.14 m^2$$

And the gain is now:

$$G_{ref} = 20 \log_{10} \left[\frac{10.14}{\frac{0.05^2}{4\pi}} \right] = 94.14 dB$$

Reflector Gain Details

Some details:

- Antennas normally have an “efficiency” factor.
  - Reflector efficiency is generally 100%
    - The reflector has no conduction or dielectric loss
  - There are some effects related to surface flatness for very large reflectors operated at very high frequencies (10 GHz and above). These effects can reduce the gain by up to 3 dB worst case.

- The “true” included angle.
  - The incident wave angle α is technically one-half of the horizontal angle corrected by an additional value due to the vertical angles between the paths. For vertical angles > 20°, the “true” included angle must be calculated and used to determine the reflector gain. The plane defined by the paths between the endpoints and the reflector is not horizontal: it is tilted. The actual angle (as seen from the reflector) is different from the angle as measured in the horizontal plane. For small vertical angles, the correction is small (as we shall see).

Reflector Gain Details

- Antenna gain is normally specified at the "far field" distance.
  - If the reflector is too close to a receive or transmit antenna, gain will be affected. In the "near field" region, interaction between the antenna and reflector cause the net gain to be reduced.
  - For reflectors and antennas in their "near field" zones, a correction factor must be applied.
  - Near/far field can be determined by: $\frac{1}{k} = \frac{\pi \times \lambda \times d}{4 \times effA}$ $\quad effA = A\cos\alpha$

    A = Reflector area in sq. feet

    d = distance between antenna and reflector in feet

    α = wave intercept angle

    λ = wavelength in feet

  - If $\frac{1}{k} \geq 2.5$ then antenna and reflector are in far field.

    Tables and formulas are available to determine correction factor.

  - For this project: $\frac{1}{k} = \frac{\pi \times 0.164 \times 4224}{4 \times 109} = 4.99$ so the reflector is in far field.

Reflector Gain Details

- Polarization rotation
  - Polarization is the alignment of the E and H fields of the electromagnetic wave with respect to a reference (the earth's surface being common).
  - The polarization must be the same at the transmitter and receiver for the maximum signal to be transferred.
  - EM waves reflected from a flat surface under certain conditions will undergo a rotation of polarization. If the shift is significant, additional attenuation will occur.
  - If the polarization rotation is significant, it can easily be corrected by rotating one of the antennas.
  - Polarization rotation increases as the angles (both horizontal and vertical) from the reflector to the endpoints increases.
  - Polarization rotation and attenuation is calculated after the final reflector position angles are determined.

Reflector gain: Large Horizontal Angle

As we observed earlier, as the included angle increases, the gain of the reflector is decreased due to the decreased effective area. Using our 16’x10’ (4.88 x 3.05 m) reflector as an example:

When α = 65° (included angle 130°) :

$$Effective\ Area = (4.88 \times 3.05) \times \cos(65^\circ) = 6.29\, m^2$$

The gain of the reflector is now:

$$G_{ref} = 20\log_{10}\left[\frac{6.29}{\frac{0.05^2}{4\pi}}\right] = 90.0dB$$

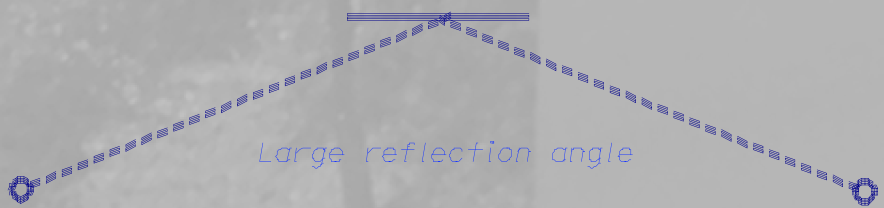
Compared to the 0° angle gain we calculated earlier:

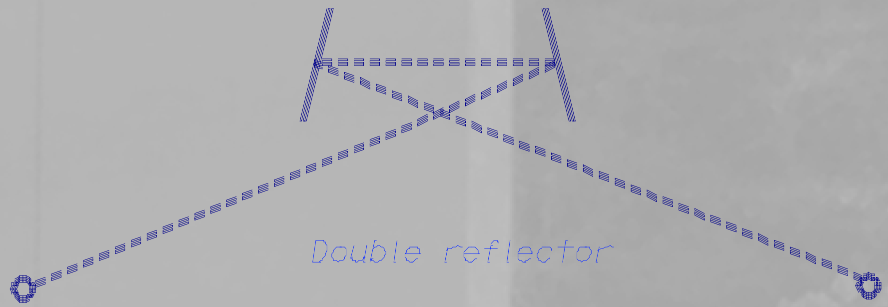
$$90.0dB - 97.5dB = -7.5dB$$

Therefore: once the included angle exceeds 130°, the path needs to be changed to reduce the reflection angles.

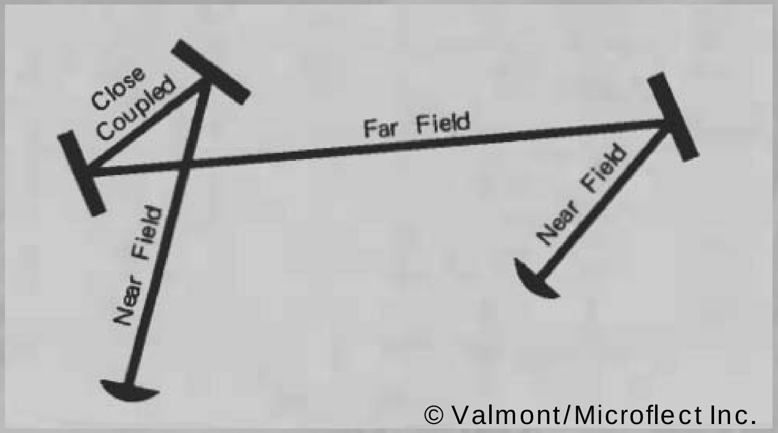
Reflector gain: Large Horizontal Angle

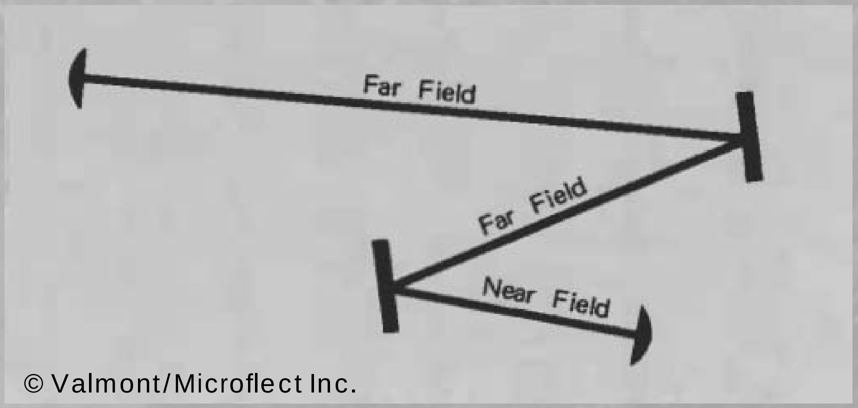
For large horizontal angles, a double reflector is used.





The possibilities are endless:





Path Calculations: Will it work?

Let us summarize the calculations:

Receiver threshold = -95 dBm
Fade Margin = 10.5 dB for 0.99999 availability
Transmit power = +10 dBm
Antenna gain (each end) = 29.0 dB
Path loss PL_1 = 119.1 dB, PL_2 = 109.9 dB
System losses = 12.0 dB
Reflector gain = 94.1

$$P_r = 10.0 + 29.0 - 119.1 - 109.9 + 29.0 - 12.0 + 94.1 = -78.9\, dBm$$

Minimum Required Pr = -95.0 + 10.5 = -84.5 dBm

Received power > Minimum required power: "It works!!"

Path Calculations: Is this efficient?

The path gain/loss equation shows two path loss values:

$$G_{ref} = P_r - P_t - G_t + PL_1 + PL_2 - G_r + L_{sys}$$

Does the reflector make up for the additional loss?

Straight line path loss for the total distance (3.1 mi.) = -122.0 dB

Total path loss for the two separate paths:

	2.3 mi. = -119.1 dB
	0.8 mi. = -109.9 dB
	= -229.0 dB
Add the reflector gain	+ 94.1 dB
Total path loss reflected path	= -134.9 dB

In this case it takes approximately 13 dB of additional gain somewhere to make up the difference. This can be higher power, larger antennas, or a larger reflector. Longer paths will result in greater losses.

But.......without the reflector there is no path..........

Reflector Position Calculations

Reflector Position Calculations

- How do we determine the physical position of the reflector?
  - Theory: the normal to the face of the reflector must bisect the true angle between the two endpoints.
    - Start with the horizontal angle between the sites.
    - Calculate the correction to the horizontal angle to compensate for the tilt of the plane containing the paths.
    - Calculate the necessary vertical angle of the reflector face.
  - The equations:

$$\tan\Delta\alpha = \tan\alpha \times \frac{\cos\theta_1 - \cos\theta_2}{\cos\theta_1 + \cos\theta_2} \qquad \tan\theta_3 = \frac{\cos\Delta\alpha}{\cos\alpha} \times \frac{\sin\theta_1 - \sin\theta_2}{\cos\theta_1 + \cos\theta_2}$$

θ_1 = smaller of the two vertical angles to endpoints

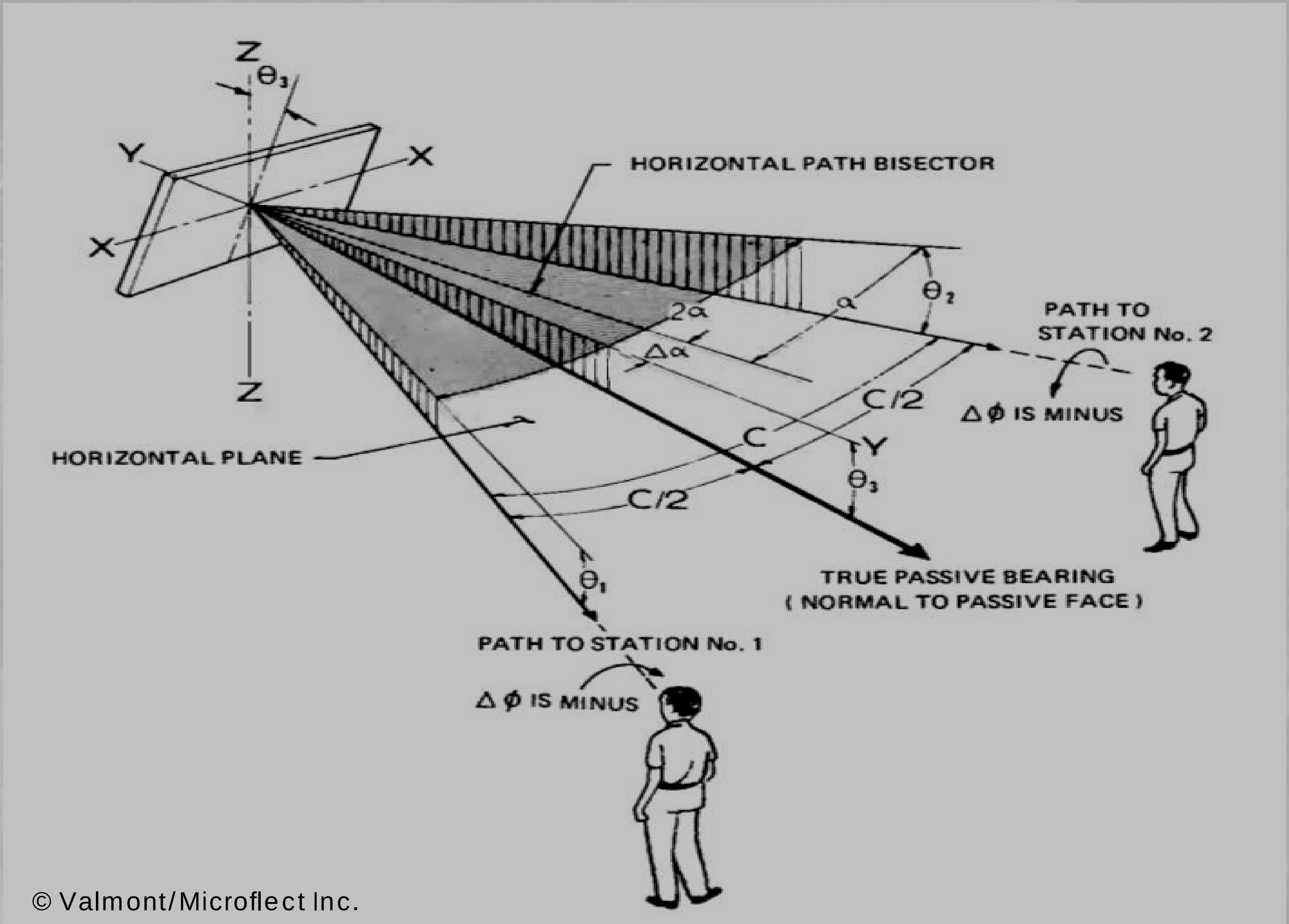
θ_2 = larger of the two vertical angles to endpoints

θ_3 = vertical tilt of the reflector

α = ½ of the horizontal angle between the endpoints

$\Delta\alpha$ = correction to the horizontal angle

Reflector Position Calculations



Reflector Position Calculations

Let’s plug in some values:

$$\Delta\alpha = \tan^{-1}\left[\tan(47.05^\circ)\times\frac{\cos(0.19^\circ)-\cos(8.55^\circ)}{\cos(0.19^\circ)+\cos(8.55^\circ)}\right] = 0.34^\circ \qquad \text{(correction angle)}$$

$$\theta_3 = \tan^{-1}\left[\frac{\cos(0.34^\circ)}{\cos 47.05^\circ}\times\frac{\sin(0.19^\circ)+\sin(8.55^\circ)}{\cos(0.19^\circ)+\cos(8.55^\circ)}\right] = 6.40^\circ \qquad \text{(vertical angle)}$$

Reflector Position Calculations

Summary of Calculation Results:

$2\alpha = 94.1°$ (horizontal angle between endpoints)
$\theta_1 = 0.19°$ (vertical angle to Fawndale)
$\theta_2 = 8.55°$ (vertical angle to Bass Mtn.
$\theta_3 = 6.40°$ (vertical tilt of the reflector)
$\Delta\alpha = 0.34°$ (correction to horizontal angle)

When adjusting the position of the reflector, the horizontal correction is always applied toward the endpoint with the smallest vertical angle.

Reflector Position Calculations

- Polarization rotation (just for drill)
  - We know polarization rotation is likely to be insignificant due to the small vertical angles.
  - The relevant equations are:

True angle between endpoints, C: $$C = 2 \times \cos^{-1}\left[\frac{\sin\theta_1 + \sin\theta_2}{2 \times \sin\theta_3}\right]$$

θ_1, θ_2 = vertical angles to endpoints
θ_3 = reflector vertical angle

Rotation of wave at each end:

$$\phi_1 = \cos^{-1}\left[\frac{\sin\theta_1 - \sin\theta_2 \times \cos C}{\cos\theta_2 \times \sin C}\right]$$

ϕ_1, ϕ_2 = polarization rotation at endpoint

$\Delta\phi$ = total rotation over the path

$$\phi_2 = \cos^{-1}\left[\frac{\sin\theta_3 - \sin\theta_1 \times \cos\frac{C}{2}}{\cos\theta_1 \times \sin\frac{C}{2}}\right]$$

Total rotation of wave over the path:

$$\Delta\phi = \phi_1 + \phi_2 - 180^\circ$$

Reflector Position Calculations

- Some numbers:

$$C = 2\times\cos^{-1}\left[\frac{\sin(0.19)+\sin(8.55)}{2\times\sin(6.40)}\right] = 94.03^{\circ}$$ (was 94.10°)

$$\cos\phi_1 = \frac{\sin(0.19^{\circ}) - \sin(8.55^{\circ})\times\cos(94.03^{\circ})}{\cos(8.55^{\circ})\times\sin(94.03^{\circ})} = 89.21^{\circ}$$

$$\cos\phi_2 = \frac{\sin(6.40^{\circ}) - \cos(47.01^{\circ})\times\sin(0.19^{\circ})}{\sin(47.01^{\circ})\times\cos(0.19^{\circ})} = 81.32^{\circ}$$

$$\Delta\phi = 89.21^{\circ} + 81.32^{\circ} - 180^{\circ} = -9.47^{\circ}$$

Attenuation due to polarization rotation: $Loss_{dB} = 10\log_{10}\frac{1}{(\cos\Delta\phi)^2}$

$$Loss_{dB} = 10\log_{10}\frac{1}{(\cos(-9.47^{\circ}))^2} = 0.12dB$$

Calculation Help

$$A_{eff} = 14.88 \cdot \cos(47°) = 10.15 m^2$$

$$\theta = \tan^{-1}\left[\frac{\cos(40.7208)\cdot\sin(40.7328) - \sin(40.7208)\cdot\cos(40.7328)\cdot\cos(0.0404)}{\sin(0.0404)\cdot\cos(40.7328)}\right] = 64.5°$$

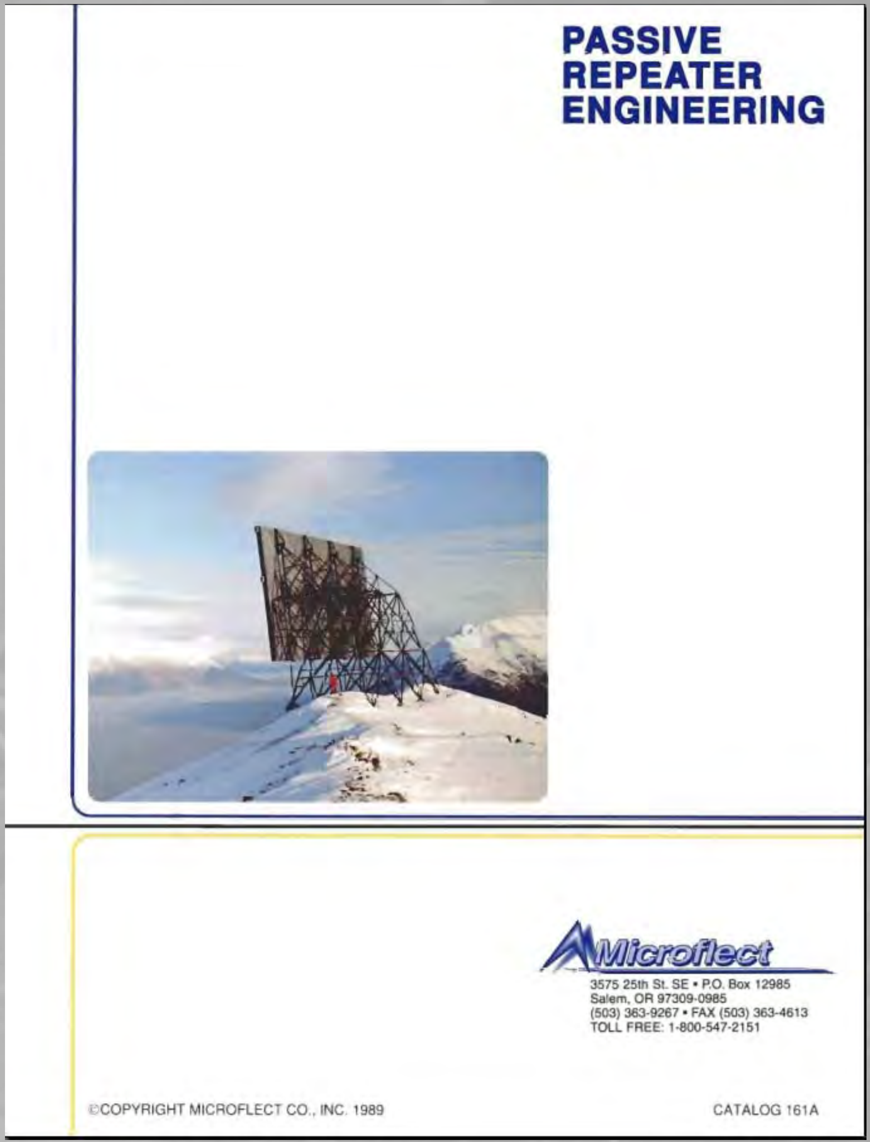
$$\frac{1}{k} = \frac{\pi\cdot\lambda\cdot d}{4\cdot a^2}$$

$$\tan\theta_3 = \frac{\cos\Delta\alpha}{\cos\alpha}\cdot\frac{\sin\theta_1 - \sin\theta_2}{\cos\theta_1 + \cos\theta_2}$$

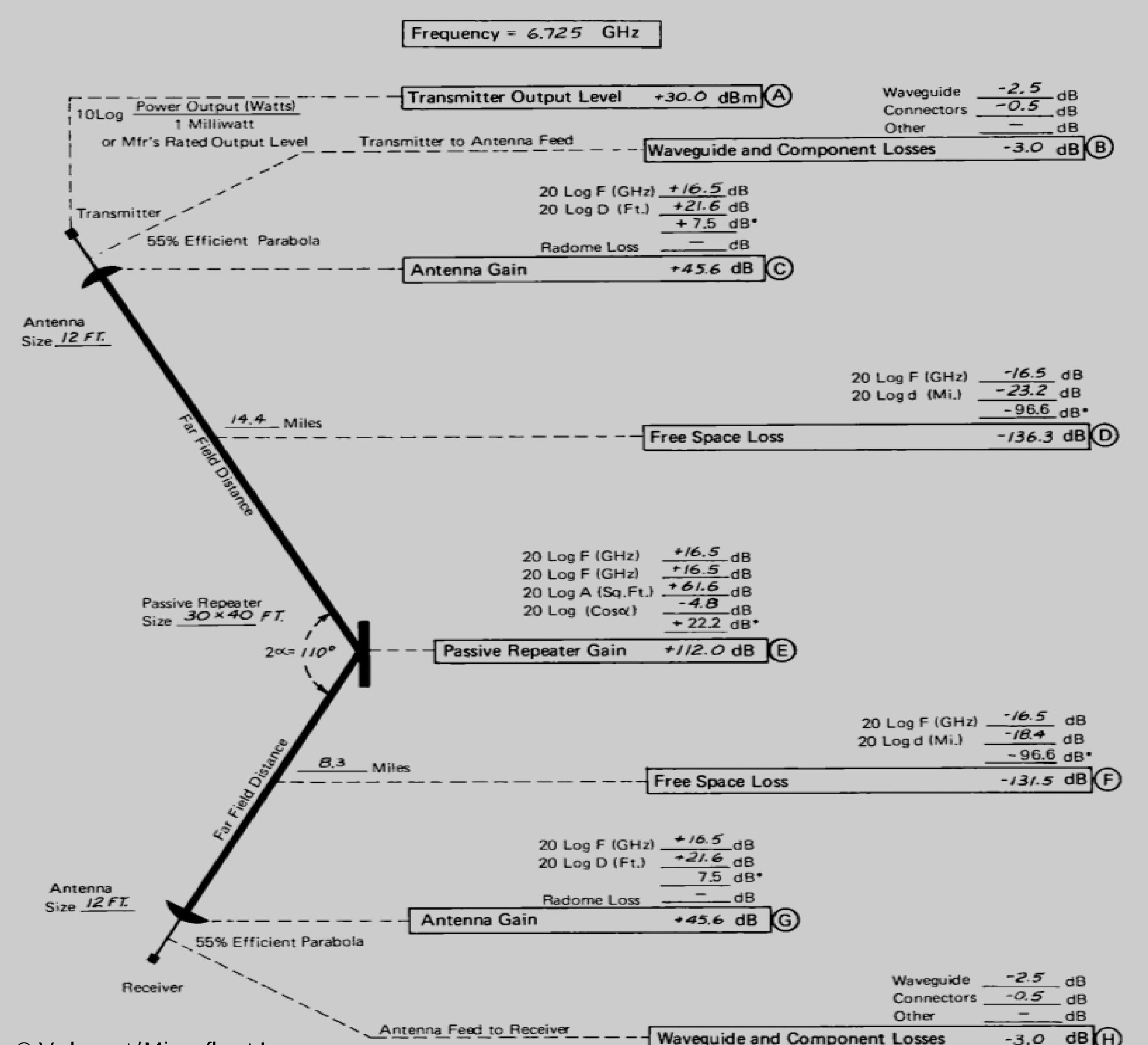
$$r_{ft} = 72.05\cdot\sqrt{\frac{dist_{mi}}{4\cdot freq_{GHz}}} = 13.2 ft$$

Help with calculations

- This is a well developed and tested technology (no magic)
    - Valmont/Microflect manual provides everything you need to know to successfully implement a reflector
    - Worksheets with examples
    - Tables and graphs to select the proper size
    - Available on the web



Help with calculations



Help with calculations

PASSIVE REPEATER BEARING CALCULATION SHEET FOR Θ_3 AND $\Delta\alpha$

Passive Size 20'x 24'	Site WEST GLACIER PASSIVE REPEATER No.1	Location NORTHWESTERN MONTANA NEAR WEST GLACIER

Horizontal included angle between paths:	2α = 68.88	degrees	
One-half the horizontal included angle	α = 34.44	degrees	
Smaller vertical path angle from horizontal: Θ_1 = 1.58		degrees	Up ☐ Down ☒
Larger vertical path angle from horizontal: Θ_2 = 11.76		degrees	Up ☐ Down ☒

$\cos\Theta_1$	= 0.9996	$\cos\Theta_1$	= 0.9996
$\cos\Theta_2$	= 0.9790	$\cos\Theta_2$	= 0.9790
$\cos\Theta_1 + \cos\Theta_2$	= 1.9786	$\cos\Theta_1 - \cos\Theta_2$	= 0.0206
$\sin\Theta_1$	= + 0.0276	$\tan\alpha$	= 0.6857
$\sin\Theta_2$	= + 0.2038	$\cos\alpha$	= 0.8247
$\sin\Theta_1 + \sin\Theta_2$	= + 0.2314		

$$\tan\Delta\alpha = \tan\alpha\ \frac{\cos\Theta_1 - \cos\Theta_2}{\cos\Theta_1 + \cos\Theta_2} = \frac{(0.6857)(0.0206)}{(1.9786)} = 0.0071$$

NOTE: $\Delta\alpha$ IS MEASURED FROM BISECTOR OF 2α

$\Delta\alpha$ = 0.41 degrees toward LASALLE

$\Delta\alpha \approx 0°25'$

$\cos\Delta\alpha$ = 1.0000

$$\tan\Theta_3 = \frac{\cos\Delta\alpha}{\cos\alpha}\ \frac{\sin\Theta_1 + \sin\Theta_2}{\cos\Theta_1 + \cos\Theta_2} = \frac{(1.0000)(+0.2314)}{(0.8247)(1.9786)} = 0.1418$$

Θ_3 = 8.07 (8° 04') degrees

(when $\tan\Theta_3$ is negative) → ☐ Up

(when $\tan\Theta_3$ is positive) → ☒ Down

Sign Convention: Cosines and tangents are positive. Sines are positive when the angle slopes downward from the passive repeater, and negative when the angle slopes upward from the passive repeater. Note that $\Delta\alpha$ always rotates the passive bearing towards the path with the least vertical angle, Θ_1.

Help with calculations

Passive Repeater Effective Area, Ae, and Polarization Rotation, $\Delta\phi$, Calculation Sheet

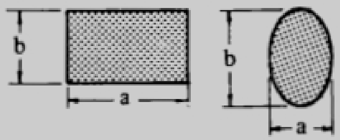
NOTE
Work these calculations in conjunction with the face angle, θ_3, and horizontal correction angle, $\Delta\alpha$, calculations.

Effective Area, Ae = (Normal Area)(cos $C/2$)

Where: C is the true angle between incident & reflected beams.

Normal Area = (a x b) for rectangular passives

Normal Area = (a x b) $\frac{\pi}{4}$ for elliptical reflectors



$$\cos \frac{C}{2} = \frac{\sin\theta_1 + \sin\theta_2}{2\sin\theta_3} = \frac{(0.4976)}{2(0.2970)} = +0.8377$$

Ae = (16)(24)(0.8377) = 321 SQ. FT.

$C/2$ = 33.10 degrees, $\sin C/2$ = + 0.5461

C = 66.20 degrees, sin C = + 0.9150 cos C = ± 0.4035

Polarization rotation $\Delta\phi = \phi_1 + \phi_2 - 180^\circ$, where:

$$\cos\phi_1 = \left[\frac{\sin\theta_1 - \sin\theta_2 \cos C}{\cos\theta_2 \sin C}\right] = \left[\frac{(\pm 0.2164) - (\pm 0.2812)(\pm 0.4035)}{(+0.9596)(+0.9150)}\right] = \pm 0.1172$$

ϕ_1 = 83.3 degrees

$$\cos\phi_2 = \left[\frac{\sin\theta_3 - \cos\frac{C}{2}\sin\theta_1}{\sin\frac{C}{2}\cos\theta_1}\right] = \left[\frac{(\pm 0.2970) - (+0.8377)(\pm 0.2164)}{(+0.5461)(+0.9763)}\right] = \pm 0.2170$$

ϕ_2 = 77.5 degrees

$\Delta\phi = \phi_1 + \phi_2 - 180^\circ$ = 83.3 + 77.5 -180° = ± 19.2°

There must be an easier way.......

- There is no shortcut to the field work.
  - Google Earth helps, but there is no substitute for physically sighting the path.

- Two options for use of present technology
  - Excel-type spreadsheet.
    - Enter the formulas and data manually
    - Need a way to validate results.
  - Specialized Application
    - (Hopefully) well tested.
    - Extra features such as terrain identification
    - Up and running with a minimum of time investment.

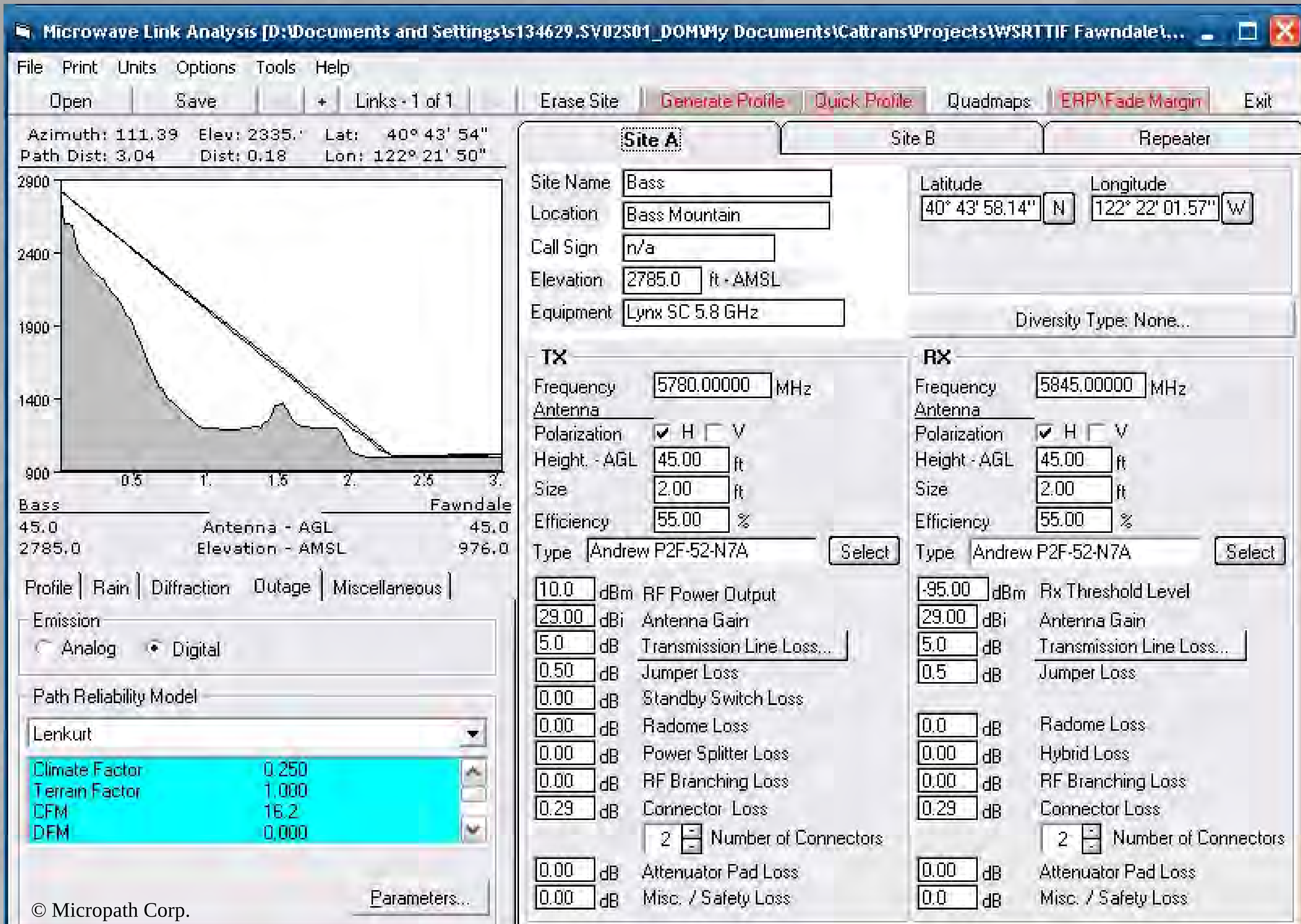
Spreadsheet: Reflector position calcs

Microwave reflector bearing calculations			**Bass - Fawndale**				
Instructions: fill in information in green boxes.							
	feet		**feet**		**feet**	**miles**	**Site ID**
Site 1 elevation	2785	Site 1 antenna height	45	dist from reflector	12144	2.3	Bass Mtn
Site 2 elevation	974	Site 2 antenna height	45	dist from reflector	4224	0.8	Fawndale
Reflector elevation	992	Height of reflector center	13				
Reflector size	10	X	16				
	degrees	**radians**					
Horizontal angle (2α)	94.10	1.64					
1/2 Horiz angle (α)	47.05	0.82					
				direction from horiz			
vertical angle Θ1	0.19	0.00		up			
vertical angle Θ2	8.55	0.15		up			
Θ3	6.40	0.11		up			
Δα	0.34	0.01	towards	Fawndale			
Reflector effective area (sq. ft.)			109.09				
True angle C	94.03	1.64					
C/2	47.01	0.82					
Polarization rotation	-9.47	-0.17	attenuation	0.12	dB		

Spreadsheet: Fade Margin

Microwave path calculations					**Microwave path availability vs. terrain and conditions variables**				
A(dB)=96.6 + 20logF(GHz)+20logD(Mi)					Undp = b * a * 10E-5 * (f/4) * D^3 * 10^(-F/10)				
path:	Bass - Fawndale (via reflector)								
link dist (D1):	2.3	miles					Mountainous, dry	Normal, interior	hot, humid
link dist (D2)	0.8	miles				climate factor (b)	1/8	1/4	1/2
Freq (f):	5.8	GHz			terrain factor (a)				
Tx pwr	10	dBm			rough/dry	0.25	99.999967	99.999933	99.999866
Rx thres	-95	dBm				0.5	99.999933	99.999866	99.999733
						0.75	99.999900	99.999800	99.999599
Path 1 loss	-119.1	dB			average	1	99.999866	99.999733	99.999466
Reflector gain	94.1	dB	size=	10x16		2	99.999733	99.999466	99.998931
Path 2 loss	-109.9	dB				3	99.999599	99.999199	99.998397
Total path loss	-134.9				smooth (over water)	4	99.999466	99.998931	99.997863
Tx TL	5.00	dB							
Tx jumpers	0.50	dB			seconds/year total	31536000	1/8	1/4	1/2
Tx connectors	0.50	dB			seconds/year outage	0.25	10.53	21.06	42.12
Rx connectors	0.50	dB				0.5	21.06	42.12	84.25
Rx jumpers	0.50	dB				0.75	31.59	63.18	126.37
Rx TL	5.00	dB				1	42.12	84.25	168.49
misc/safety	0.00	dB				2	84.25	168.49	336.98
						3	126.37	252.74	505.47
Antenna gain	29.00	dB				4	168.49	336.98	673.96
Total gain	68				minutes/year outage	0.25	0.18	0.35	0.70
Total loss	-146.93					0.5	0.35	0.70	1.40
						0.75	0.53	1.05	2.11
Receive Sig	-78.93					1	0.70	1.40	2.81
Fade Margin (F)	**16.07**					2	1.40	2.81	5.62
						3	2.11	4.21	8.42
						4	2.81	5.62	11.23

Specialized Application: PathAnal



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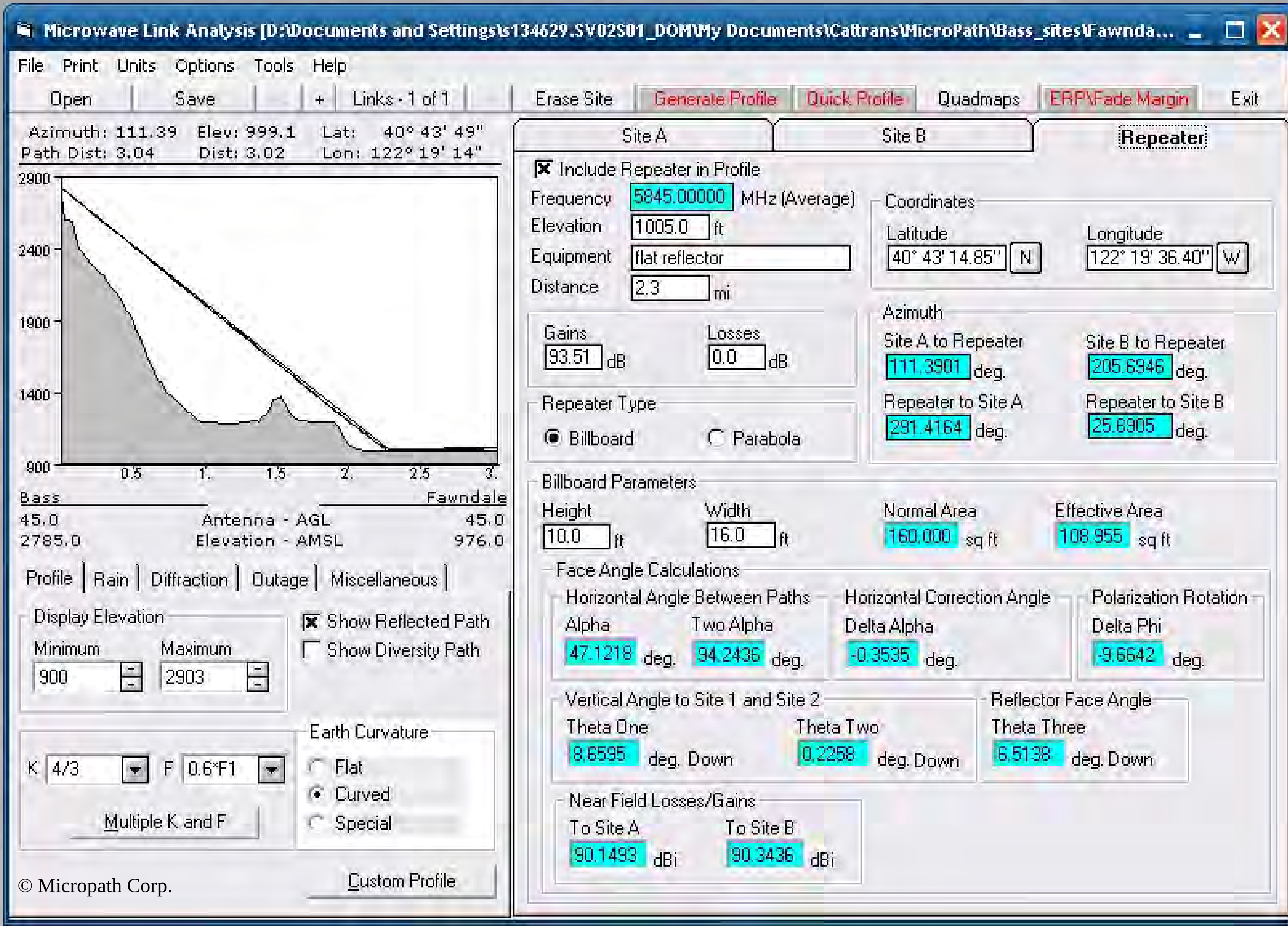
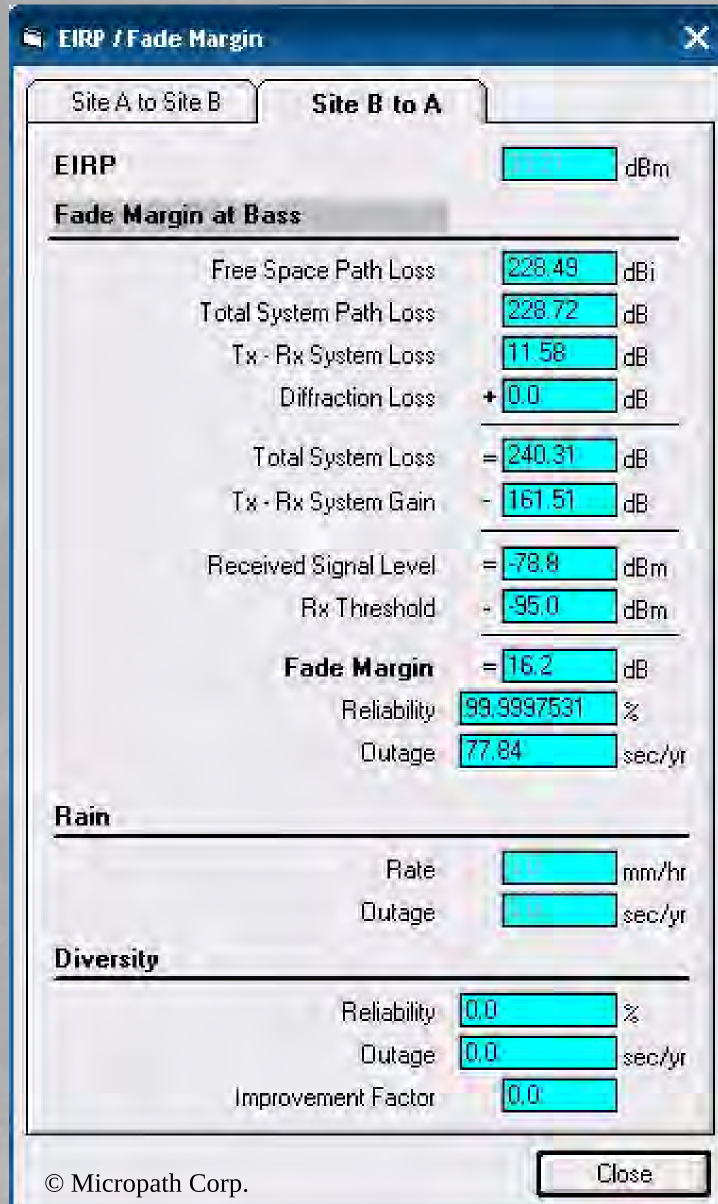
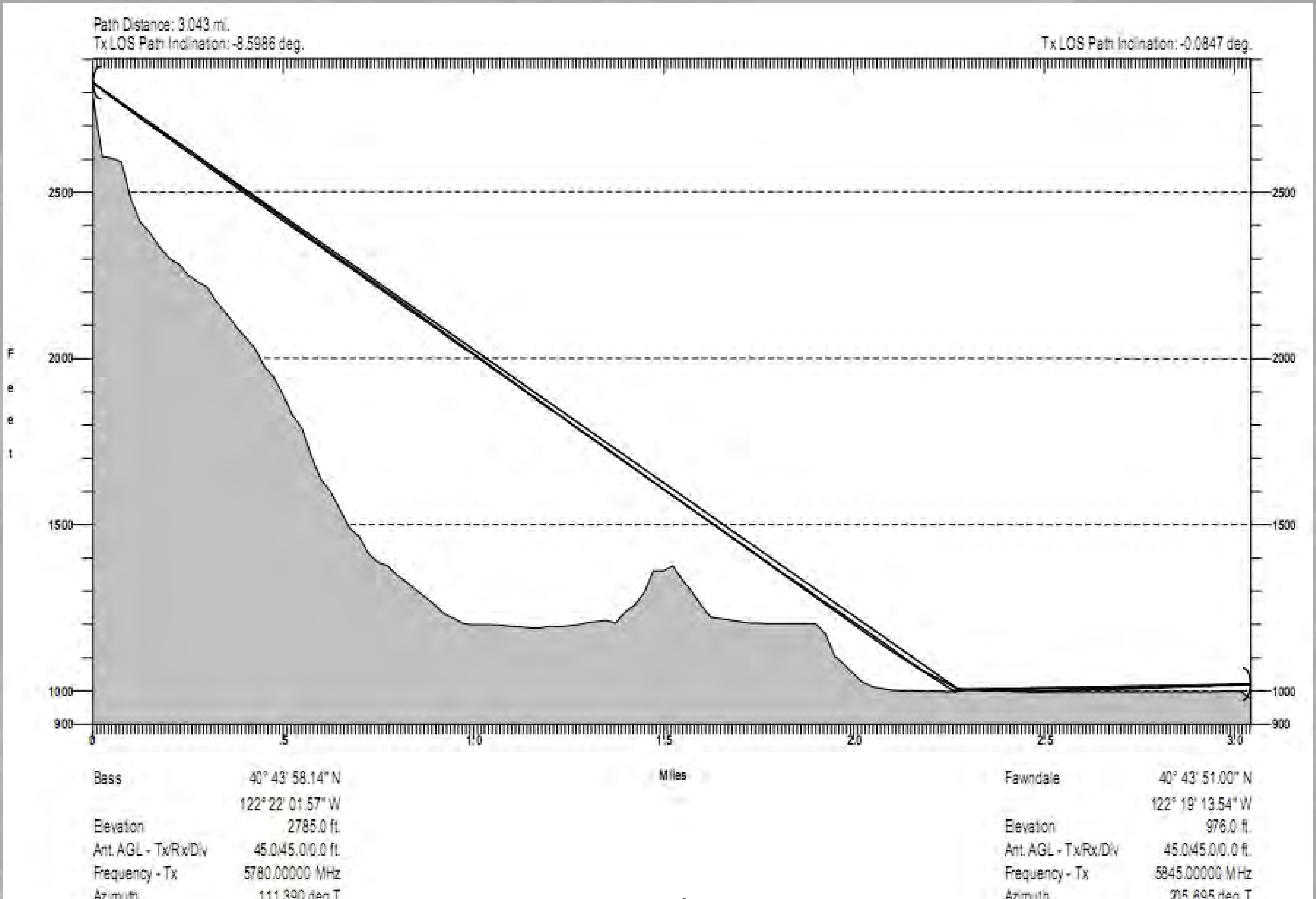
Specialized Application: PathAnal



Specialized Application: PathAnal



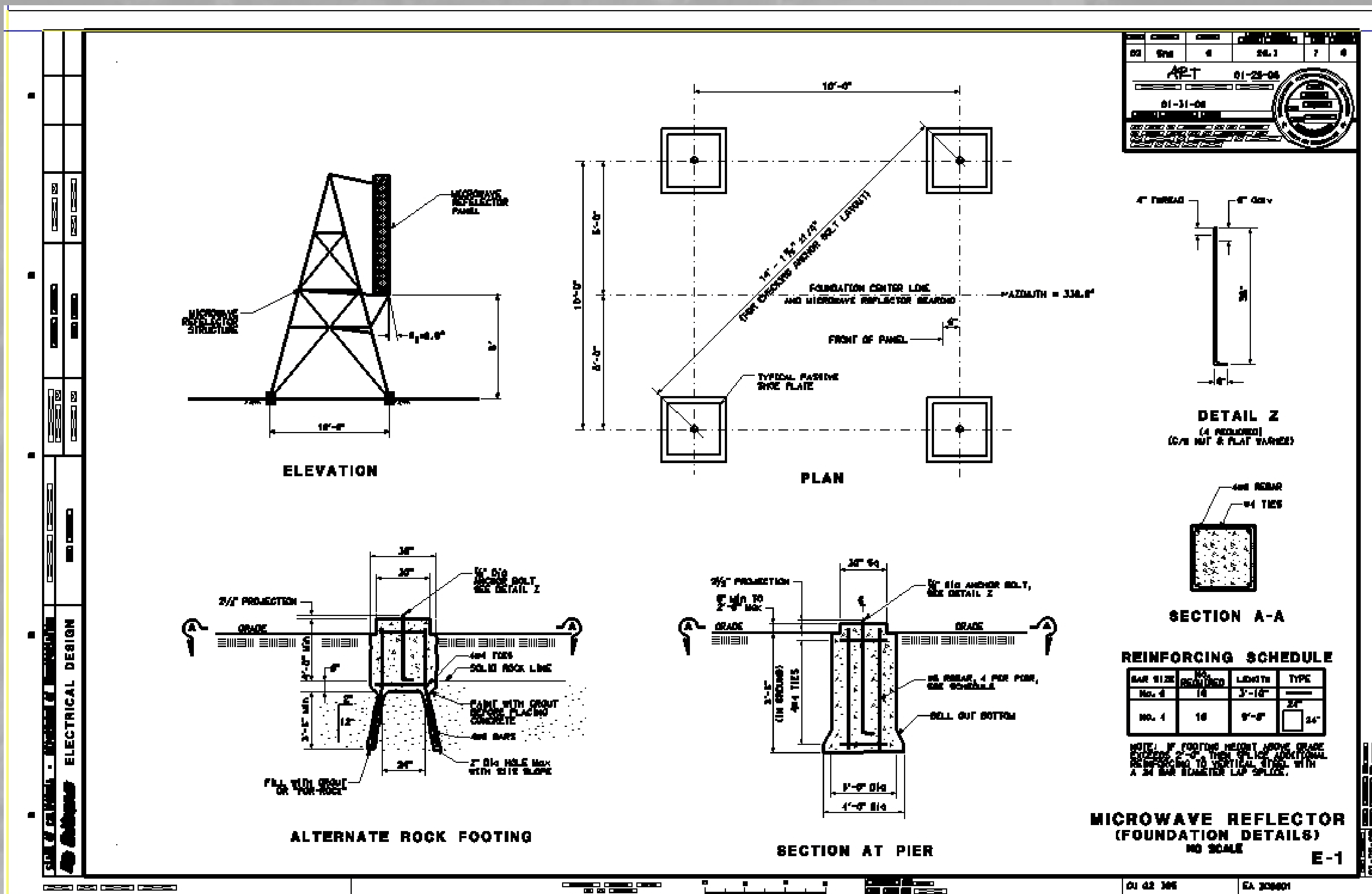
Specialized Application: PathAnal



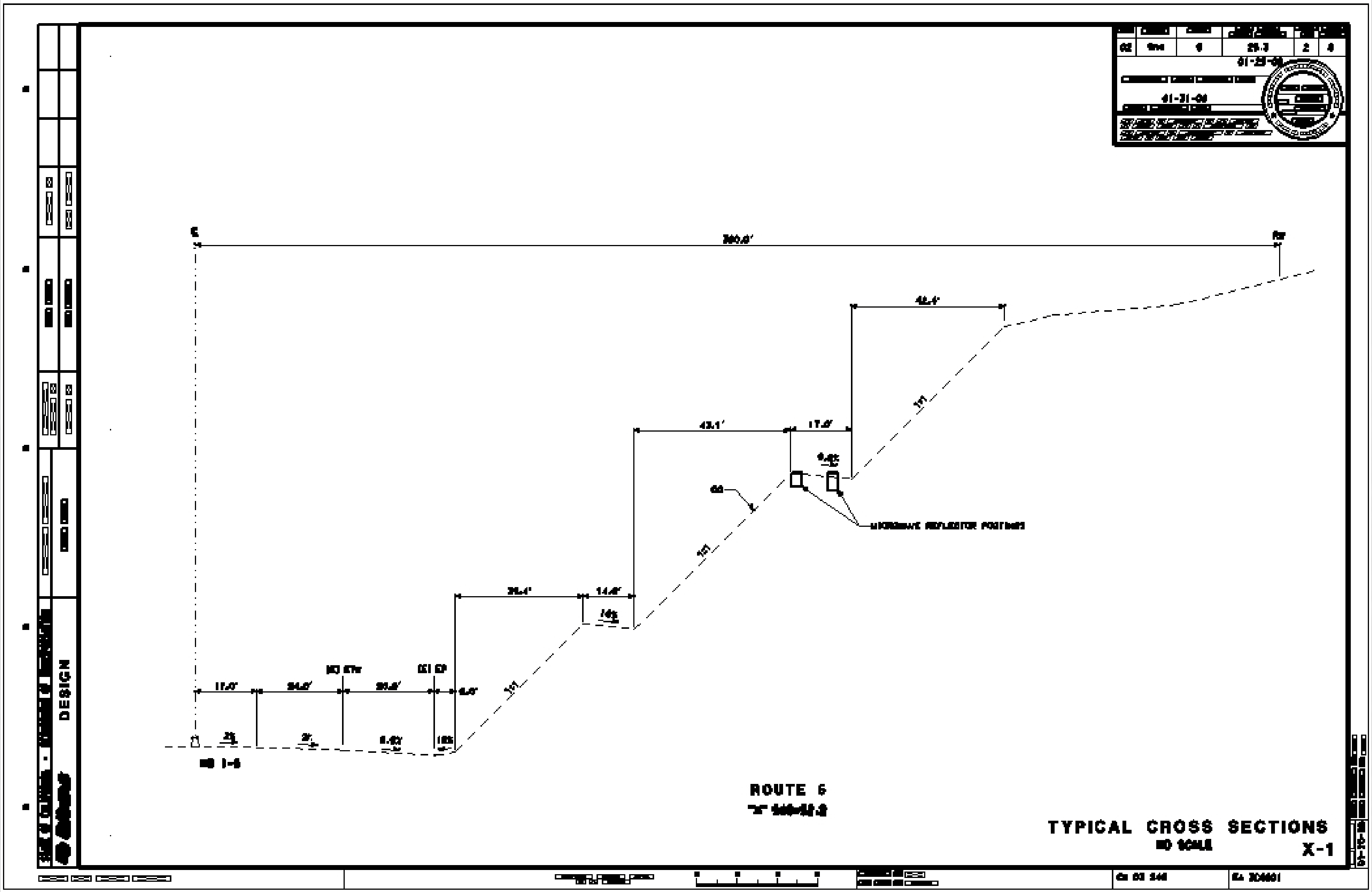
The Physical Stuff

We have everything we need on paper, but it is only useful if it exists in the real world......

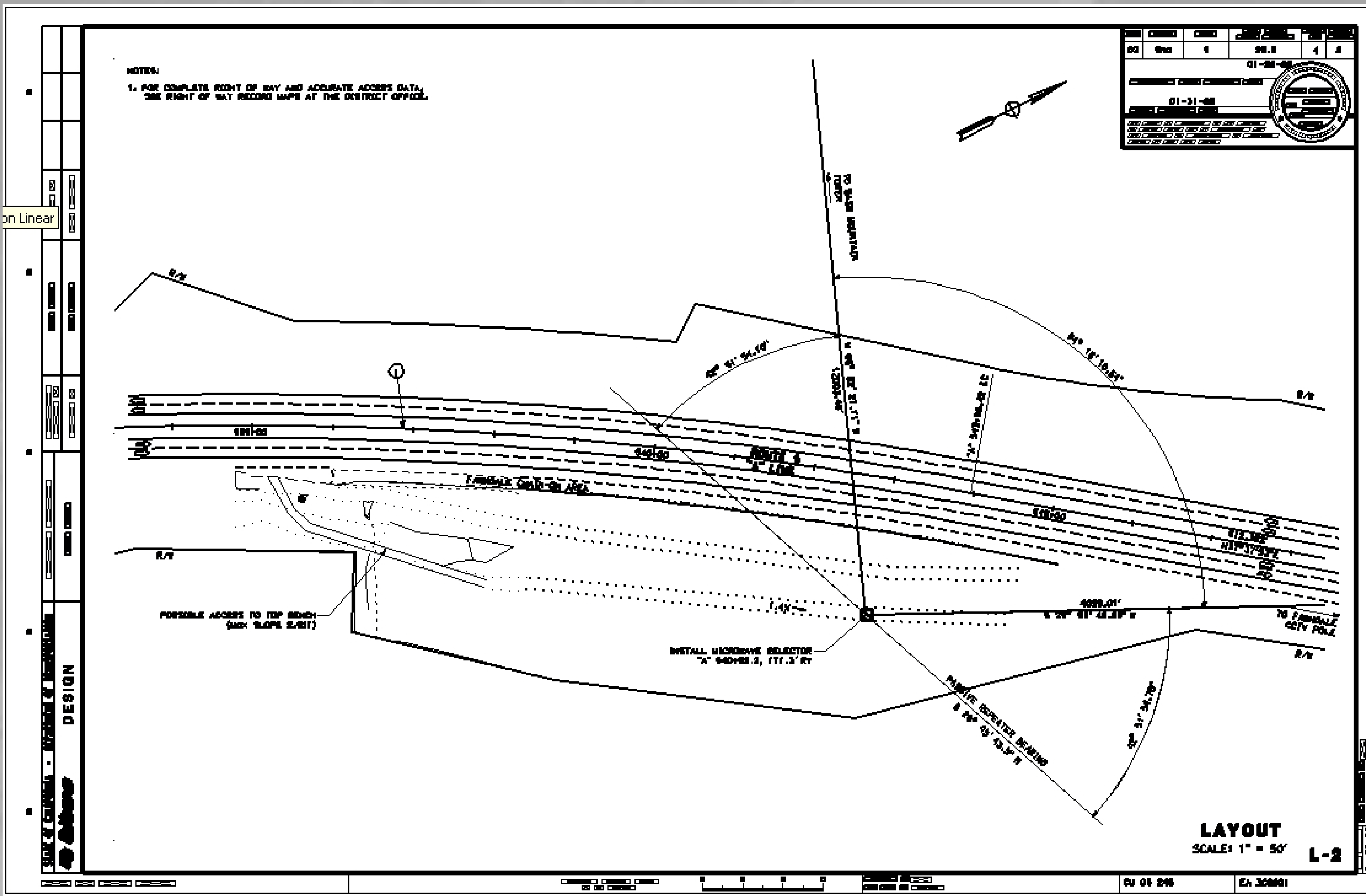
Everything Begins with a Good Foundation



Everything Begins with a Good Foundation



Everything Begins with a Good Foundation



Some Challenges

- Unusual location
  - Limited access
    - Steep angle
    - Unpaved, loose soil
- Contractors
  - May not be familiar with this type of equipment
    - Plans must be clear and concise
    - Include test conditions and specifications
    - Scheduling time for test
      - Have endpoints set up ahead of time
  - Adjustment Procedure
    - Well documented
      - Dependent upon accurate site measurements and calculations

Construction

Construction

Construction

Construction

Construction

Construction

Construction

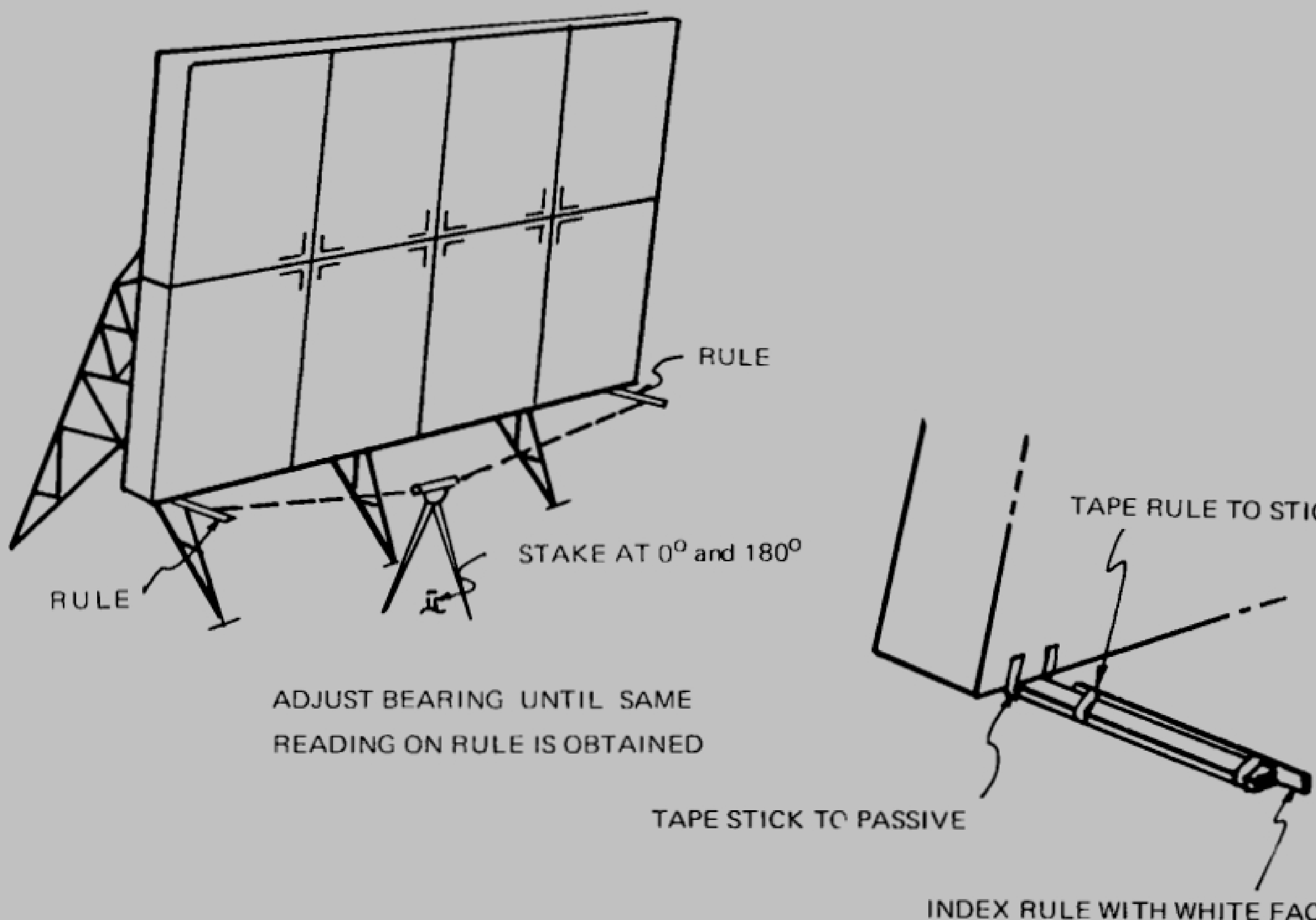
Adjustment: Equipment

- Use of transit/theodolite with digital readout
  - Measures horizontal and vertical angles
  - Allows measurement of differences on each side of center

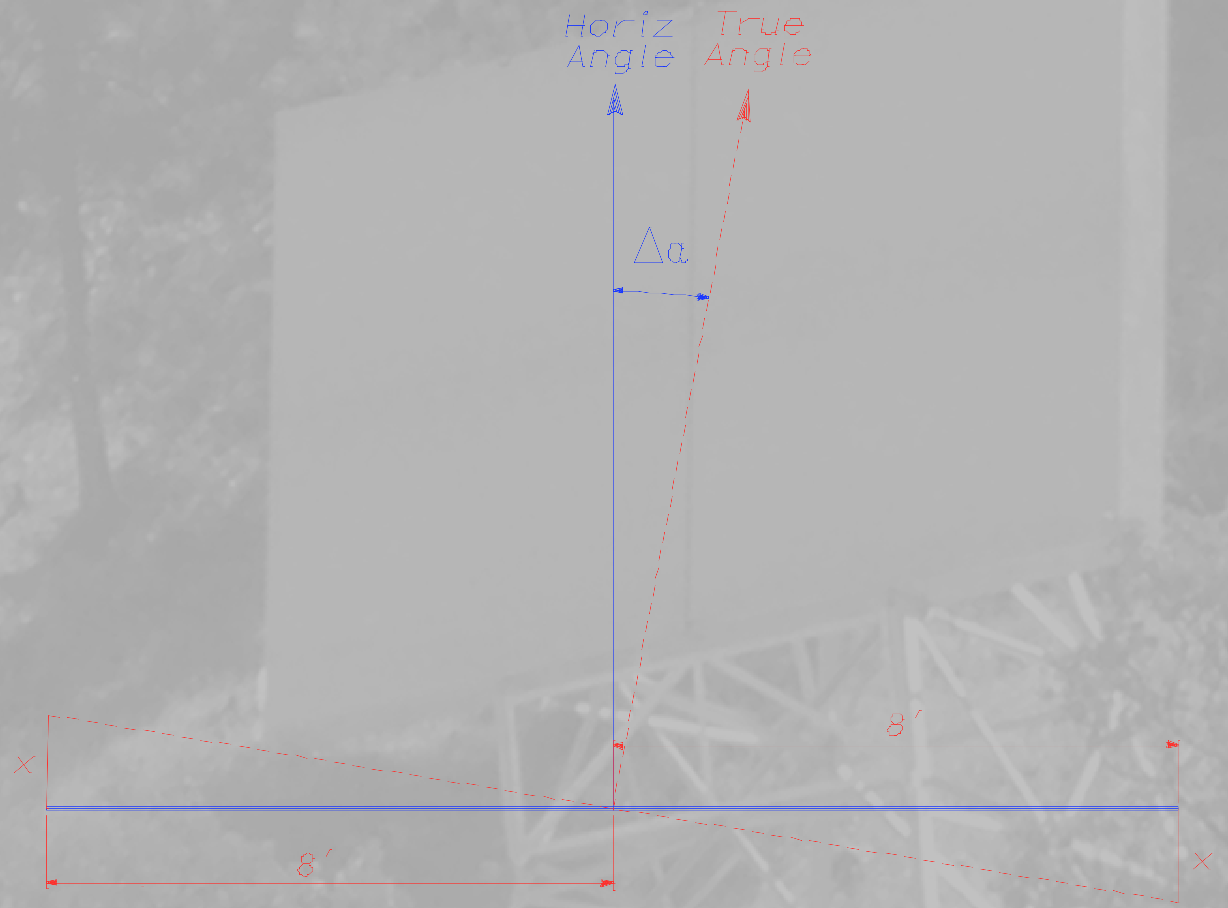
- Adjustment “sticks” attached to reflector
  - Provides measurement from each corner of the reflector

Adjustment: Reflector setup

Adjustment: Horizontal Angle



Adjustment: Horizontal Angle Correction



$$x = 8 \times 12 \times \tan(0.34^\circ) = 0.57''$$

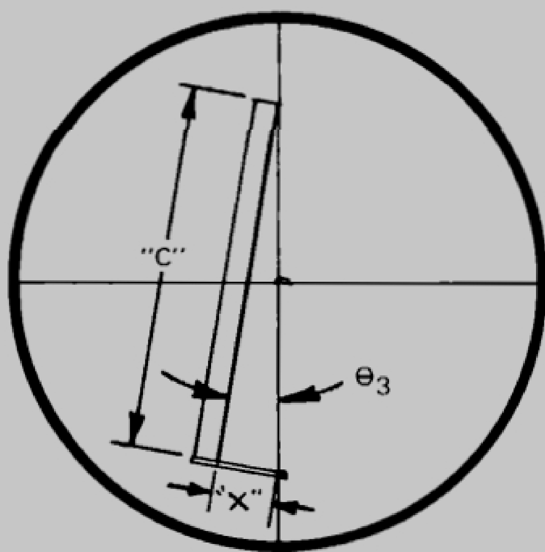
Total difference between readings = 1.14”

Adjustment: Vertical angle

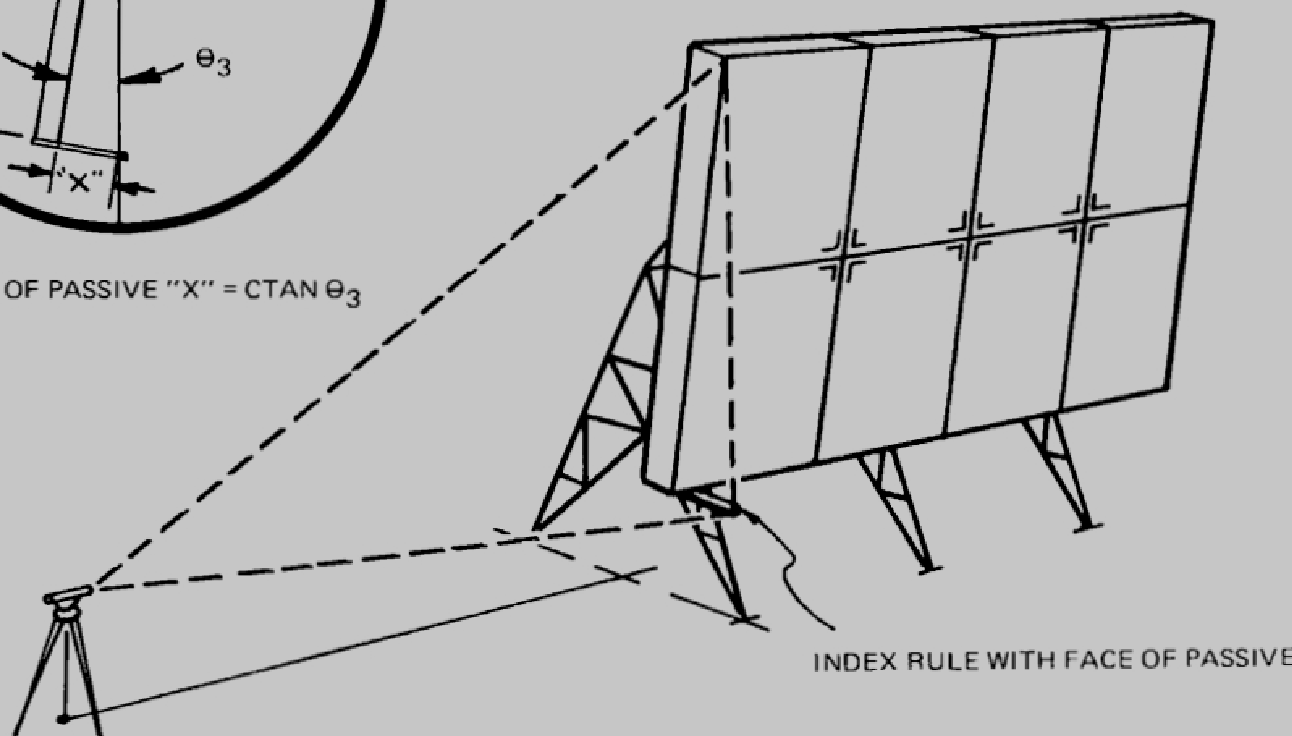
$$\theta_3 = 6.40^\circ \ (up)$$

$$x = 10' \times 12'' \times \tan 6.40^\circ = 13.5''$$

$$(Upper\ stick\ is\ longer)$$



END VIEW OF PASSIVE "X" = CTAN Θ_3



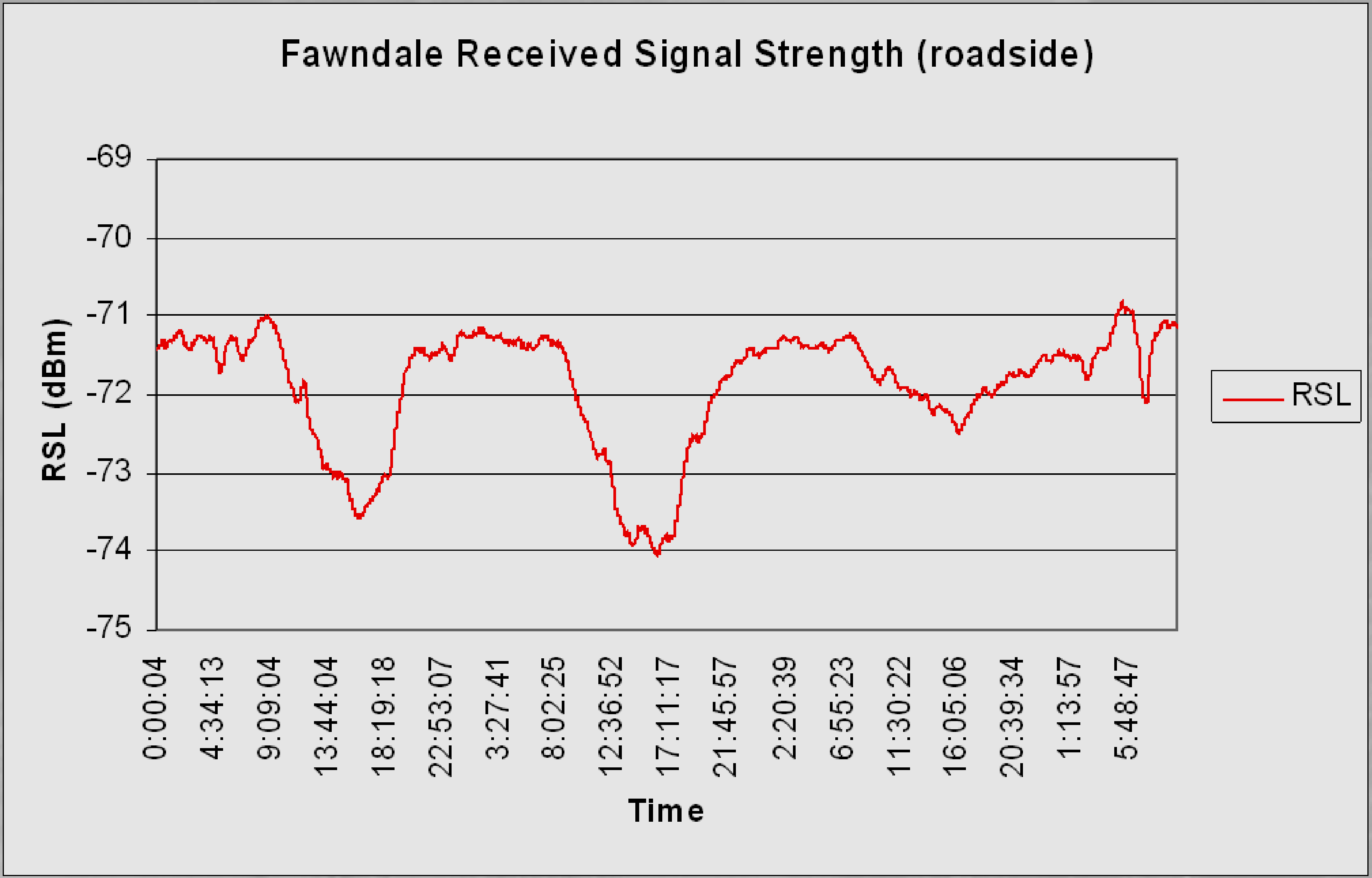
Adjustment: Mechanics

- Lower adjustment rods used for both horizontal and vertical adjustment
  - Upper arms are attached after final position is set.
  - Adjustment range is limited
    - Foundation location is critical

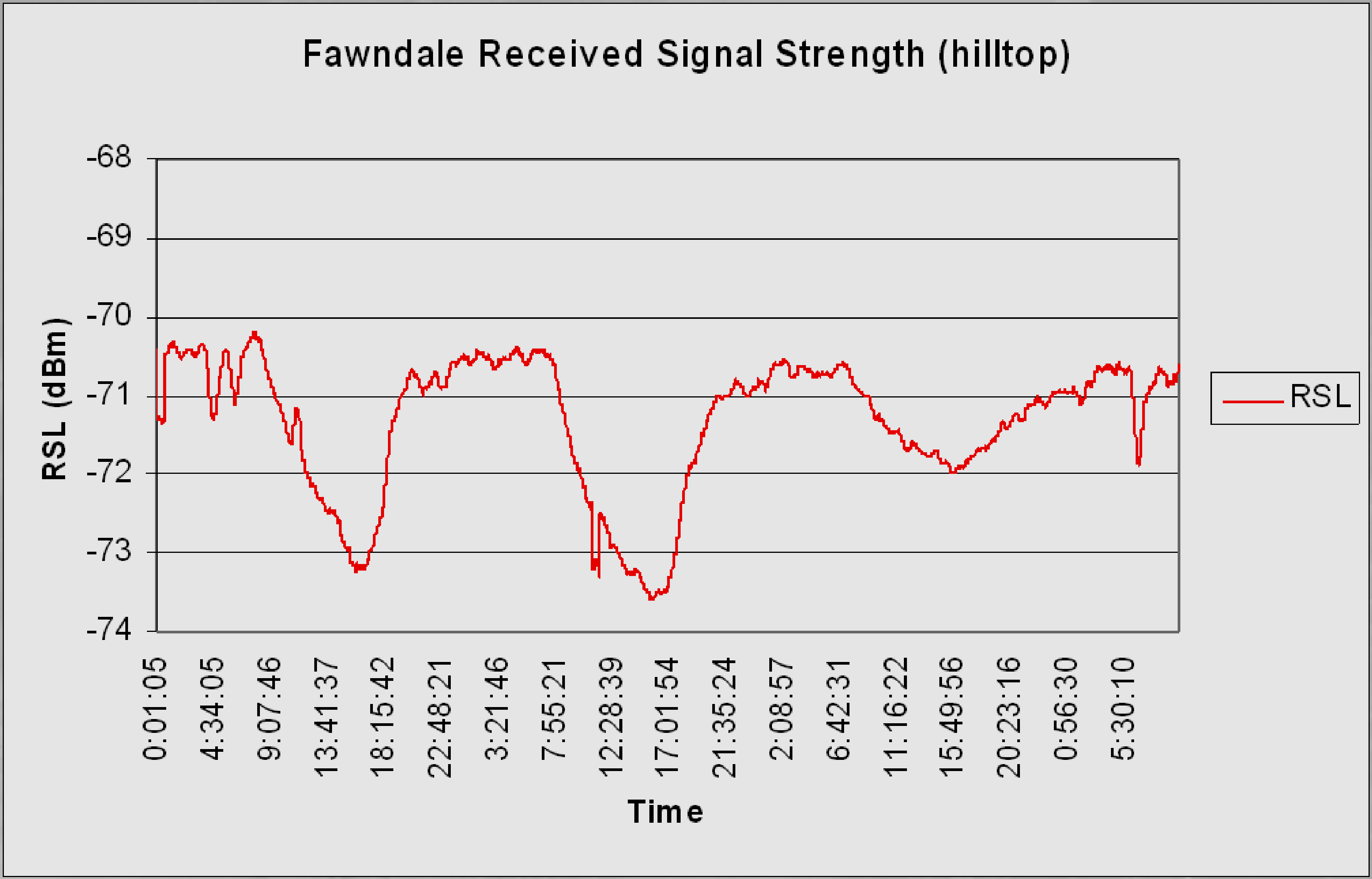
Results

- Initial testing
  - Received signal level within ± 3dB of calculated
- Long term performance
  - Remote monitoring of signal level at both ends
    - Variance will occur due to atmospheric conditions
      - Generally stronger in the morning
  - Stable link
    - No known outages over almost 2 years of operation
      - Link is running with an extra +5 dBm of power

Results: Signal Strength



Results: Signal Strength



Cost: Isn't this Expensive?

- Total cost of reflector + installation was ≈ $88K
  - This is a one-time cost with virtually zero maintenance.
  - There can be considerable savings when compared to long term ongoing costs for cellular or ISDN charges
    - Much higher bandwidth over this type of link
  - Reliability: there is nothing to break
  - Advantages in inclimate climates
    - No need to access in the dead of winter
    - Extreme ice conditions can be handled

Summary

- Just because a remote site is not within “line of sight” does not mean it cannot be accessed via microwave radio.
  - Highways tend to be in canyons
  - Right of way many times will include locations well above the roadway level
  - A reflector can be put in locations that would be impractical for an “active” repeater
    - No power required
    - No maintenance or repair
    - No regular access needs to be maintained
    - Reliability of the passive repeater, properly installed, will be 100%

Thank You

- Every project requires the support of lots of folks, without whose assistance no project would be successful.

- Caltrans
  - Art Robles, P.E., Caltrans Electrical Design
  - Mike Mogen P.E., Caltrans Civil Engineering Design
  - Gary Meurer, Caltrans ITS Electronic Technician
  - Ian Turnbull, P.E., Chief, Office of ITS Engineering and Support
  - Ken Vomaske, P.E., Caltrans Construction

- Contractors and Suppliers
  - Valmont/Microflect Inc. (Supplier)
  - Schommer & Sons (Installation contractor)

Questions & Comments

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