Path Selection and Propagation Prediction

for Millimeter Wave Operation

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April 2020
50 MHz & Up

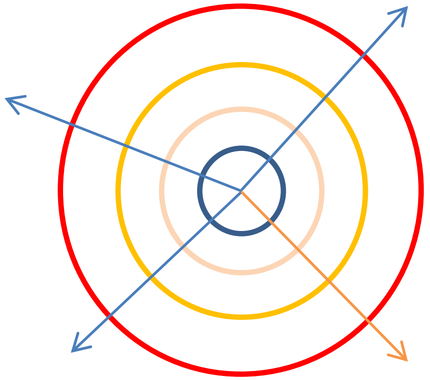
Outline

- **Review: Free Space Path Loss & the Link Budget**
- **Overview: Propagation at cm & mm waves**
- **Site Selection & Orientation to Target**
- **Predicting mm wave "Openings"**

For the easier cm wave and shorter mm wave contacts,
we don't need to use every last one of these techniques

Free Space Path Loss

- **Free space path loss** is the spreading loss as a signal radiates outward in all directions from its source
  - no atmospheric effects
  - no blockage

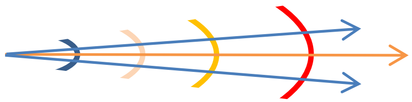


FSPL $_{\text{(in dB)}}$ = -92.5 - 20 log Range $_{\text{(in km)}}$ - 20 log Freq $_{\text{(in GHz)}}$

- $1/R^2$, 10x **distance** increase, FSPL increases **100x** (20 dB)
- $1/F^2$, 10x **frequency** increase, FSPL increases **100x** (20 dB)

GHz	100km
10	**-152**
24	**-160**
47	**-166**
80	**-171**
123	**-174**
134	**-175**
241	**-180**

Antenna Gain



- Gain antennas focus their Rx/Tx beam into a narrow fraction of the sphere

dBi gain = +18.2 + 20 log Diameter (in cm) + 20 log Freq (in GHz)

- **2x** frequency = **4x** more gain (+**6** dB)
- **2x** diameter = **4x** more gain (+**6** dB)
- **2x** diameter *or* **2x** frequency = **half** the beam width (**harder to point**)

Band	D = 60 cm (2’)		D = 120 cm (4’)	
GHz	Gain (dBi)	Beam (deg)	Gain (dBi)	Beam (deg)
10	**34**	**3**	**40**	**1.5**
24	**41**	**1.3**	**47**	**0.65**
47	**47**	**0.66**	**51**	**0.33**
80	**52**	**0.38**	**58**	**0.19**
123	**56**	**0.25**	**62**	**0.13**
134	**56**	**0.24**	**56**	**0.12**
241	**61**	**0.13**	**67**	**0.06**

System Gain

- Credits
  - Tx Power (dBM)
  - Tx Antenna (dBi)
  - Rx Antenna (dBi)
- Debits
  - Thermal Noise Floor (-174 dBm in 1 Hz)
  - Rx Noise Figure (dB)
  - Rx Bandwidth (10 log BW) (eg, -34 dB for 2500 Hz SSB)

$$\text{Gain}_{\text{dB}} = \text{Tx}_{\text{dBm}} + \text{Tx}_{\text{dBi}} + \text{Rx}_{\text{dBi}} - \text{NF}_{\text{dB}} - \text{BW}_{\text{dB}} - 174_{\text{dBm}}$$

Typical System Gains

At higher bands, system gain drops & antenna pointing is harder

- Antenna Gain goes up @ higher bands
  - If we keep size constant (but it does get harder to point)
  - With an antenna at each end, we get double the dBs
- Tx Power, Rx NF get worse @ higher bands
  - *Higher band (80 GHz and up) numbers below are optimistic*
  - *2500 Hz SSB BW assumed; narrower modes (CW, digital) have better gain*

GHz	60cm Dish	Tx dBm	Rx NF	Sys Gain
10	34	40	1	**247**
24	41	35	2	**256**
47	47	30	4	**260**
80	52	20	6	**257**
123	55	-3	10	**236**
134	56	-4	11	**236**
241	61	-12	20	**222**

Link Budget
Signal/Noise = System Gain – Path Loss

- **System Gain overcomes Path Loss to deliver Signal**
- System Gain falls as we go to higher bands
- Path Loss increases as we go to higher bands ($1/F^2$)
  - And I haven't talked about extra losses yet!
  - Above 20 GHz, moisture and weather hit us harder and harder
  - At 122 GHz, we also get hit by oxygen
- **Result: SNR (or max range) falls as we go to higher bands**

By the way, we can 'measure' Sys Gain = observed SNR + calculated Path Loss

  - *Use several paths on good WX days to find System Gain*
  - *Then predict SNR for a new path using new calc PL and measured Sys Gain*
  - *New SNR will decrease by the same amount that PL increases*

- **Our strategy:**

Choose the path & forecast the weather so as to reduce path loss

(and use low BW modes … like CW & digital)

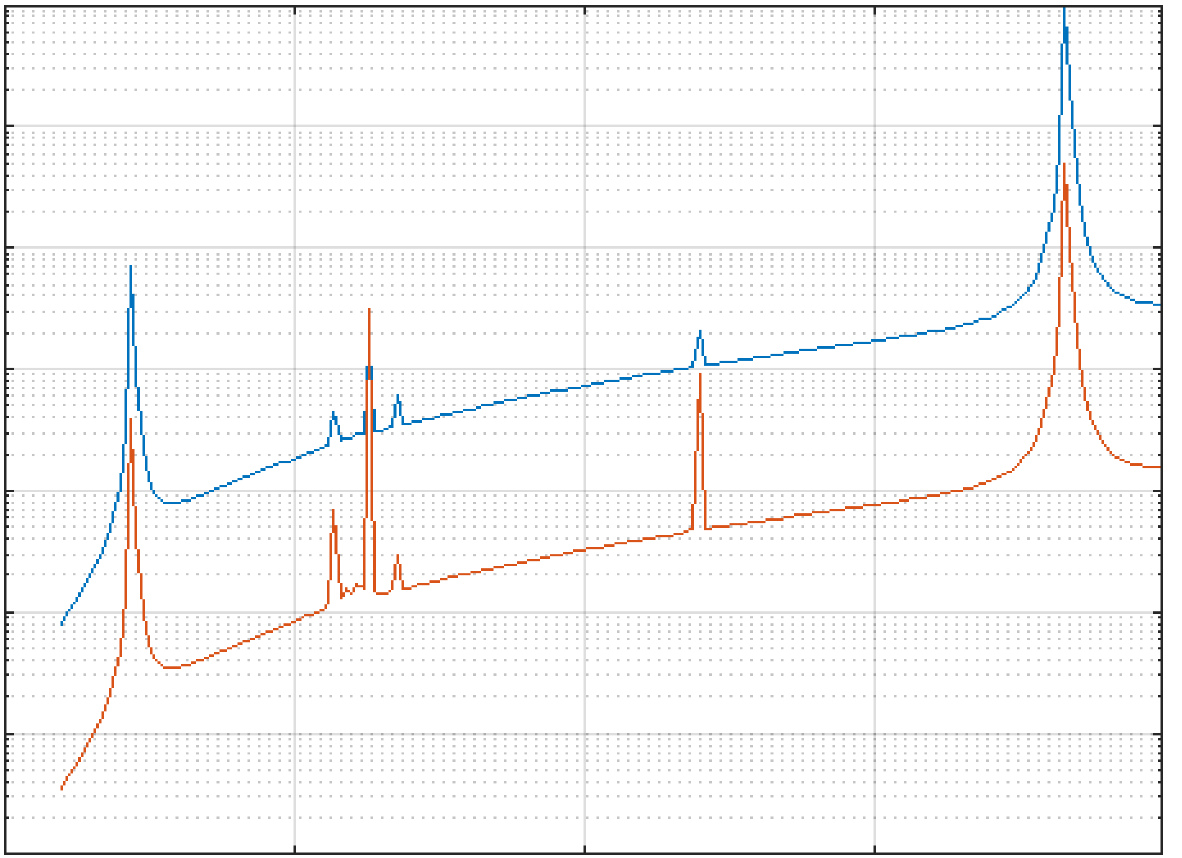
An Overview of Propagation

(at centimeter & millimeter waves)

- **Line of Sight Path (FSPL) is the baseline**
  - Things mostly go downhill (extra losses) from there
- Obstacles Always Hurt
  - Foliage, Buildings, Hills, Earth's Curvature (loss or total blockage)
  - Bounces and Knife Edge Refraction can get us around blockages
    - But they have extra losses and generally take a longer path
- Atmospheric Refraction Helps
  - Air temp decreases with elevation: "4/3 earth radius" extends horizon blockage point
  - Ducting enhancements/temperature inversions can go even further
- **Atmospheric Losses --- dominate at mm waves**
  - Vary with altitude and weather along the path; increase with freq > 20 GHz
  - Atmospheric Gas attenuation (water vapor, oxygen)
  - Clouds, Rain, Fog, etc attenuation
- Scatter
  - Aircraft, Rain, Snow, Clouds, Tropo
- Multipath

Atmospheric Gas Loss

(an issue above 20 GHz; dominates above 50 GHz)



Blue curve for 68F, 50% RH, sea level
Orange curve for 60F, 10% RH, 4700' ASL
It tells us that for best mm wave DX,
go to the mountains in extremely dry weather

Elevation	0'	4700'
Air Temp, RH	68F, 50%	59F, 10%
Band		
10	-1.5	-0.6
24	-19	-3
47	-14	-2
80	-36	-5
123	-103	-23
134	-106	-13
241	-363	-40

- **Extra dB/100km above 20 GHz**:
  - dB/R, not just $1/R^2$
  - **Dominates beyond 25-40 km**
- Water Vapor (humidity)
  - **Steady upward trend**
  - **Resonances at 22 & 183 GHz**
  - Tends to be drier at higher elevation
- Oxygen
  - **Resonances at 60 & 119 GHz**
  - Lower air pressure at higher elevation (less O_2)

Clouds, Rain, etc

- Rain loss >>> moisture loss
  - Drizzle 2-3x H_2O dB loss; moderate rain 10x H_2O dB loss
- Rain scatter best @ 10 GHz
  - Rain WX radars operate in S and X bands; good match to size of rain drops
  - Above 10G, rain scatter increases, but mainly as a focused **forward** scatter; over 100G, acts like a very focused lens
  - The useful scattering volume is likely surrounded by excess moisture, drizzle and clouds (very lossy at higher bands)
  - Except for in-line forward scatter, scatter lengthens the path
- Cloud loss >> moisture loss
  - Cloud WX radars run in the 35-95 GHz range

- Conclusion: avoid rain, fog & clouds

Other Scatter Modes

- Aircraft scatter: doppler increases, strong forward scatter focusing
- Tropo scatter: high scatter loss, great DX if you have excess system gain (cm waves)

References
(Microwave Propagation)

- http://www.mike-willis.com/Tutorial/propagation.html
- www.mike-willis.com/Tutorial/RT%20Propagation%20Lecture.pdf
- http://www.wa1mba.org/papers/WA1MBA%20Super%20VHF%202019%20Scattering%20Talk.pdf Rain Scatter
- https://bobatkins.com/radio/troposcatter.html
- http://w3sz.com/PackRats.html
  - aircraft scatter 9/2013
  - troposcatter 9/2014
- Google these ITU Recommendations:
  - P.676 (atmospheric gas loss)
  - P.453 (refractive index)
  - P.530 (terrestrial LOS)
  - P.834 (tropo refraction)
  - P.838 (rain attenuation)
  - P.840 (clouds and fog)

Tools for calculating path loss

- ITU P.676 atmospheric gas loss model has been coded up by:
- http://weather.vk5microwave.net/Calculate.aspx
- members.inode.at/576265/Linkbudget.zip at OE2IGL's website
- https://www.mathworks.com/help/phased/ref/gaspl.html
  (caveat emptor; I found a bug in their library code)

SPOILER ALERT:

We will use this model plus weather forecasts to hunt for "openings"

I wrote my own spreadsheet to plot SNR curves vs Td & Ta for P, R, F

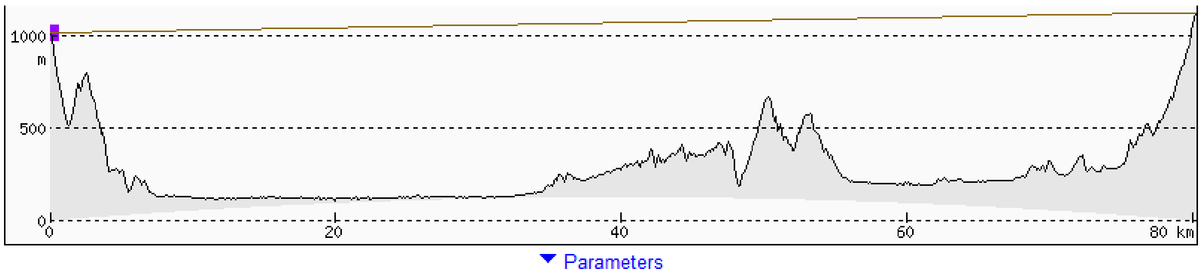
Selecting the Path

- Find an LOS Path of desired length
  - High end points with drop offs & clear horizons are best
  - Beware mid-path obstructions and earth curvature
- Tools
  - https://www.heywhatsthat.com/
  - https://k7fry.com/grid/
  - Both mark paths as overlays on Google maps
    - Terrain & Roads view (orientation landmarks)
    - Satellite view
    - Street view (check for foliage, other obstuctions)
  - Both give path length, bearing
  - HeyWhatsThat adds elevation, LOS check, path profile, panorama view

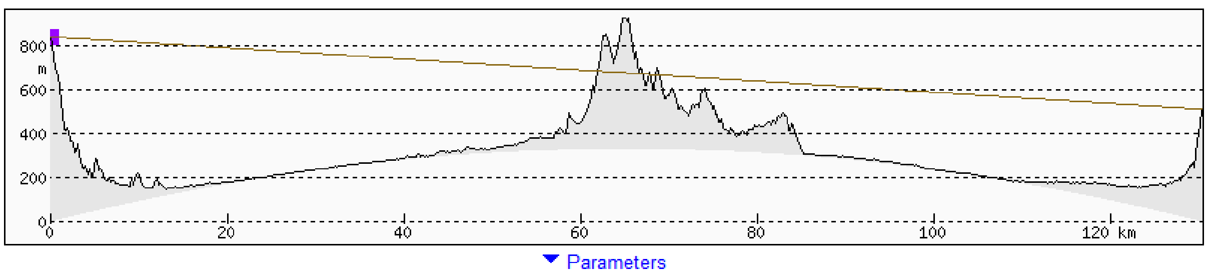
- Visit the sites and vet them for foliage, obstructions, takeoff angles

Start with a Line Of Sight (LOS) Path

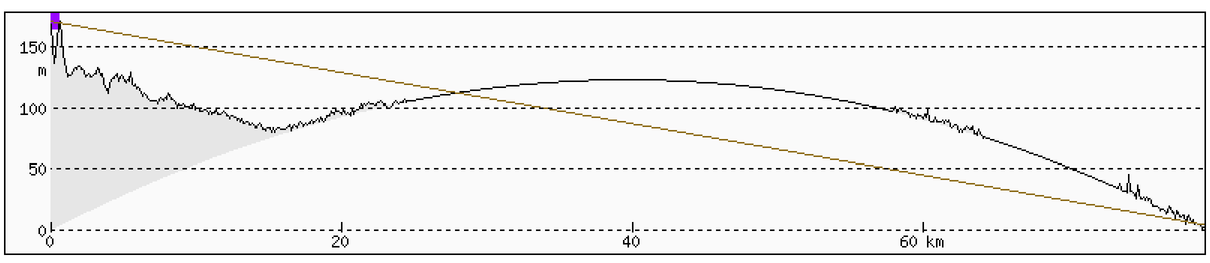
HeyWhat'sThat Elevation Profiles



YES! Both ends high



NO Obstructions



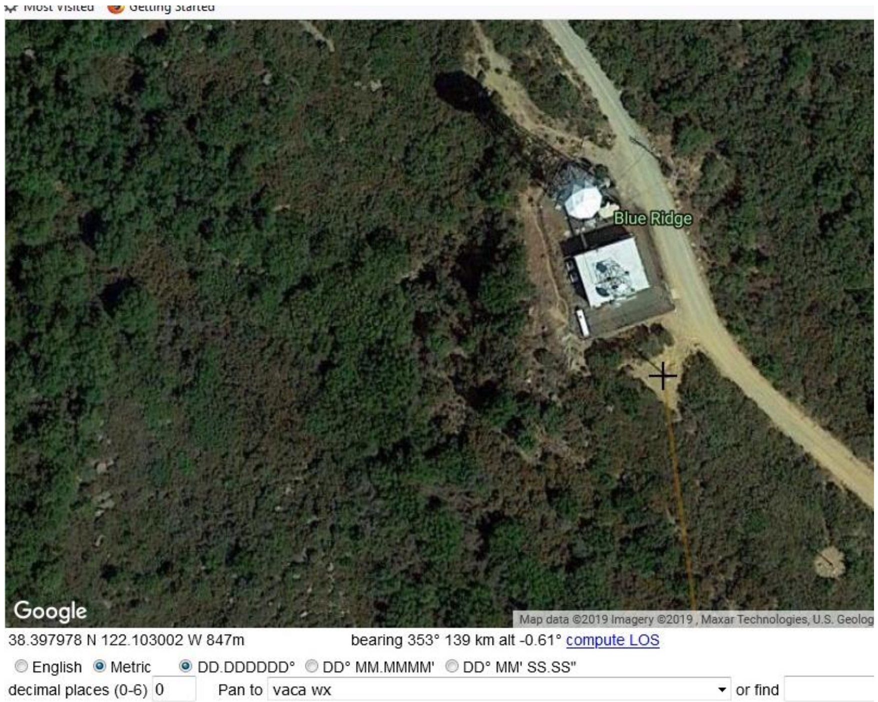
NOT below horizon

(HeyWhat'sThat has refraction option)

On Site: Alignment to Target

We are talking fraction of a degree beam widths @ mm waves

- Binocs & Smartphone/Tablet
  - Compass, GPS in mobile device for rough orienatation
  - HeyWhat's That, k7fry plan views
  - Hunter Theodolite mobile app
  - https://www.peakfinder.org/ horizon view (AR)
    - Precise orientation using foreground and horizon landmarks
- Rifle Scope pre-aligned to beam
- Lower band radio pre-aligned to higher band radio
  - Higher SNR at lower band (40-60 dB)
  - QSY and bingo!



Alignment Tools

Hey What's That – bearing, elevation, horizon

Plan view of path to target relative to roads

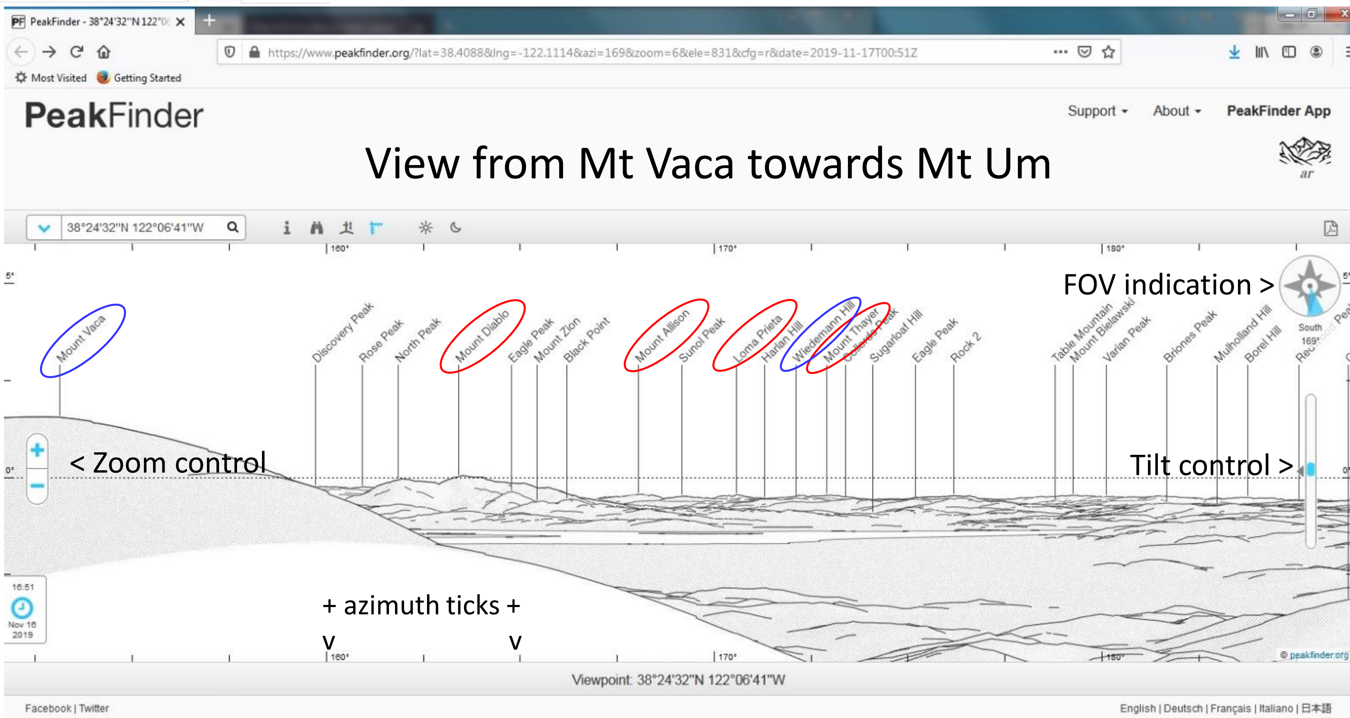
Structures & trees.

Peak Finder:

Augmented reality

Runs on smartphone/iPad

Uses compass, GPS to orient line drawing of horizon & foreground landmarks



Forecasting an “Opening”

- In this case, “an opening” is “not a closing”
- We’re looking for a reduction in moisture losses
- ITU P.676 Model tells us loss in dB/km = *f* (Td, Ta, F, P)
  - Td, dew point = absolute water vapor content
  - Ta, air temp (Relative Humidity = *f* (Ta, Td))
  - Frequency
  - P, air pressure, tracks elevation
- We predict S/N Ratio from Sys Gain, FSPL, Atmo Loss
- Or look for the WX we need to deliver desired S/N

Reducing path loss *or* Finding "Openings"

(122 GHz examples)

In descending order of importance (1 > 2 > 3 > 4)

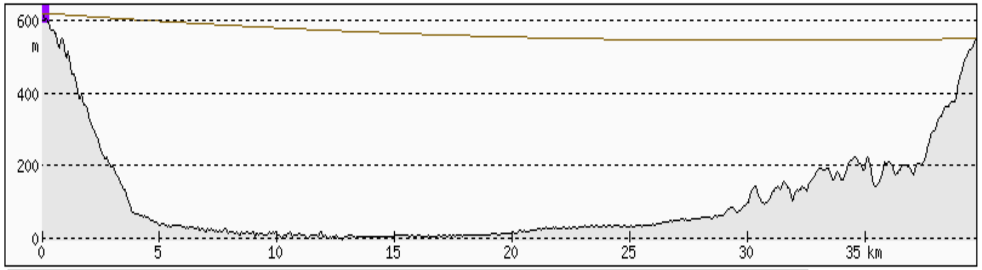
1. Find two mountains with LOS … the higher the better …
   - More distant horizon
   - Lower water content
   - Lower (oxygen) pressure

2. Look for a ***very low dew point*** day (T_{dew} < **-20 ^{o}C**)
   - *Dew point* is the air temp at which water saturation (dew, fog, mist, rain) occurs
   - Dew point is a *direct* (*absolute*) measure of how much water vapor is in the air
   - Looking for a **dry air duct** between the two mountains
   - Beware: path "sags" in middle (usually wetter)

3. Look for high dew spread (T_{air} – T_{dew}) = low *relative* humidity (RH)
   - RH (or dew spread) measures how close we are to saturation at current air temp (*not* how much water)

$T_{air} - T_{dew}$	RH	Weather
0 ^{o}C	100%	Dew/frost/rain…
10 ^{o}C	~45%	Everyday
20 ^{o}C	~22%	Pretty Dry
30 ^{o}C	~11%	Verrrrrry Dry
40 ^{o}C	~6%	Bone Dry

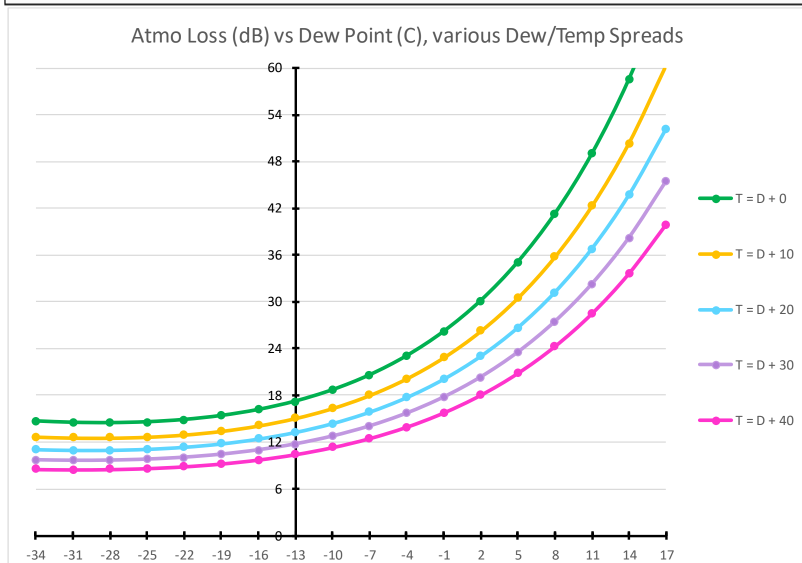
4. Use the top end of the band to get away from the 119 GHz O_2 absorption line.



40 km QSO

(Sierra Rd – Windy Hill)

K6ML <-> KB6BA

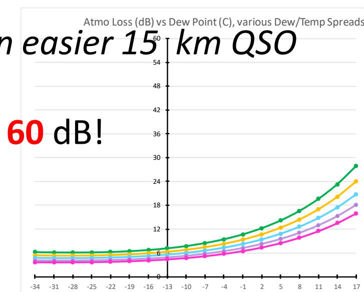


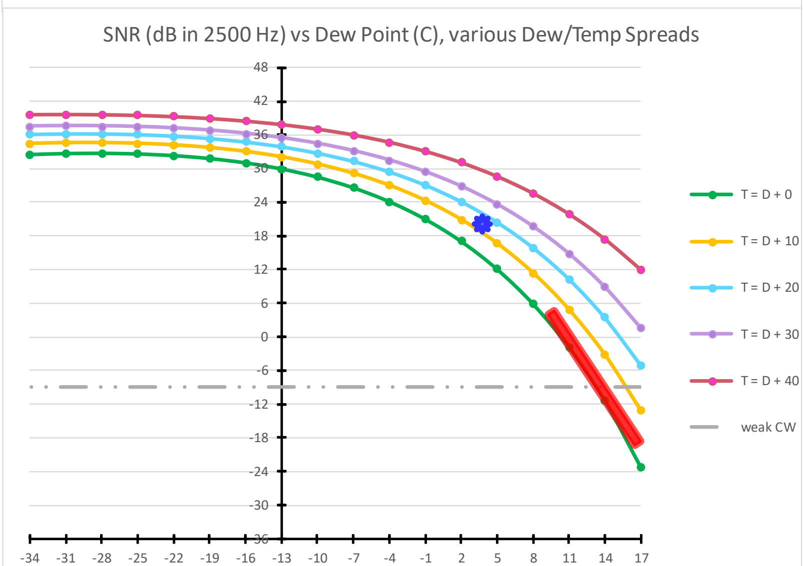
Atmospheric Loss (in 1 "S" unit steps) vs Dew Point (in 3 ^oC steps) for various Dew/Temp spreads (in 10 ^oC steps)

- 2 S units for < -13 ^oC T_d & 20 ^oC spread
- Over 10 S units when not dry

Compared to ………………………….an easier 15 km QSO

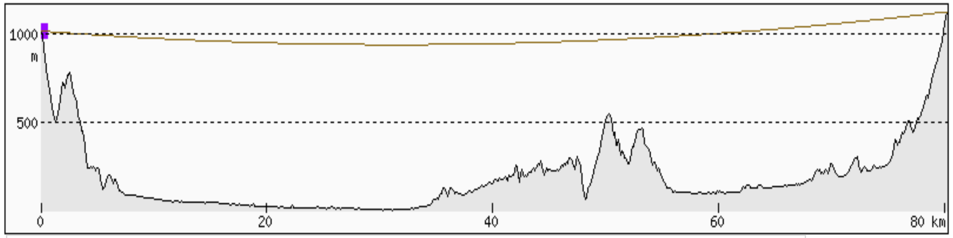
- FSPL went up **8** dB (to 166 dB)
- Atmospheric loss went up **6** to **60** dB!





SNR (dB), assuming a 213 dB system gain

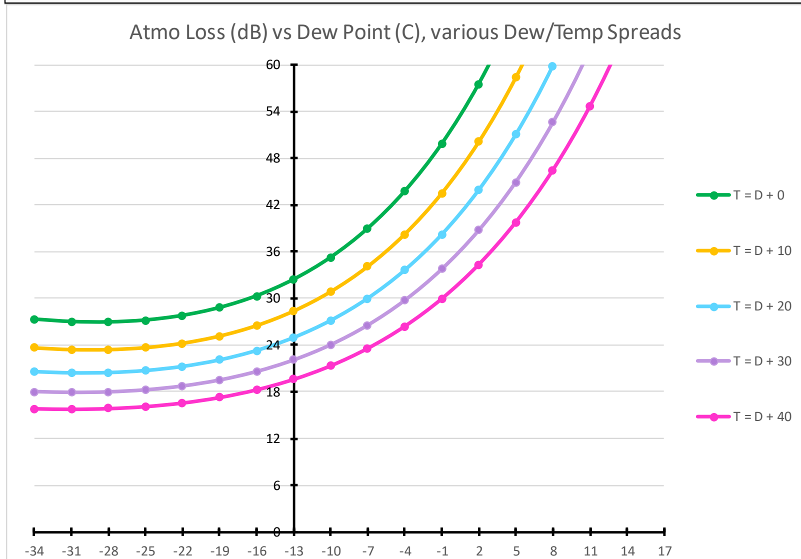
- Dashed grey line is weak CW copy
- Dry days are "S6-S7" copy
- A wet day can shut this path down
  - Our first attempt failed (eve. dew)
  - Next day was dry and strong signals



80 km QSO

(Umunhum - Diablo)

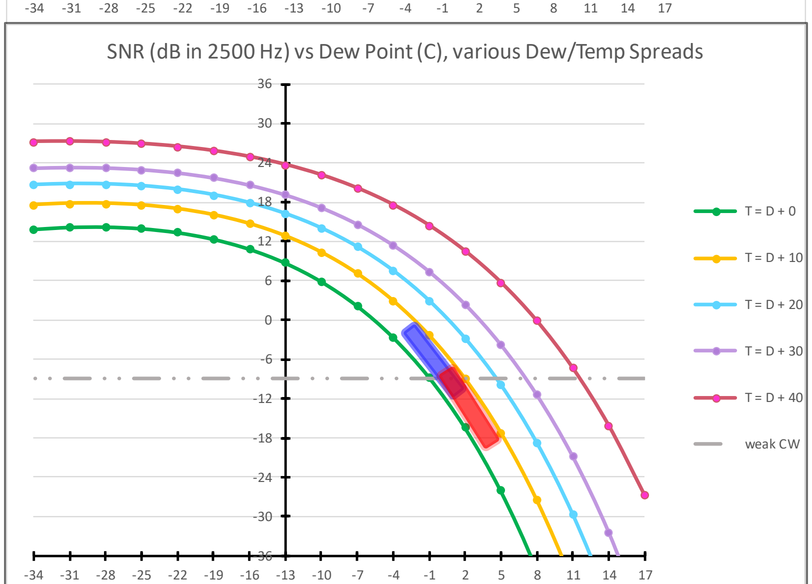
K6ML <-> KB6BA



Atmospheric Loss (in 1 "S" unit steps)
vs Dew Point (in 3 ^{o}C steps) for various Dew/Temp spreads (in 10 ^{o}C steps)

- 4 S units for -13 ^{o}C T_d & 20 ^{o}C spread
- Well over 10 S units when not dry

- 2x distance, FSPL goes up **6** dB (172 dB)
- Atmospheric loss went up **12** to **>100** dB
- The weather can easily shut us down



SNR (dB), again assuming a 213 dB system

- Dashed grey line is weak CW copy
- Dry days are "S3" copy…
- Even a bit of moisture drifting across any part(s) of the path shuts us down

Haze/moisture rising at mid path

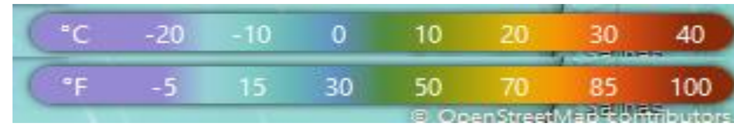
(Sunol Ridge, caused QSB and dropouts)

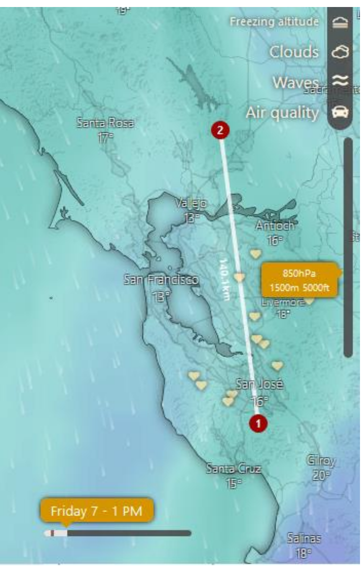
Searching for the perfect wave …

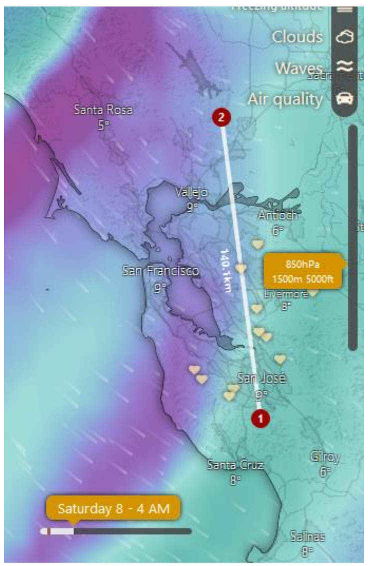
Searching in time & 2-D space

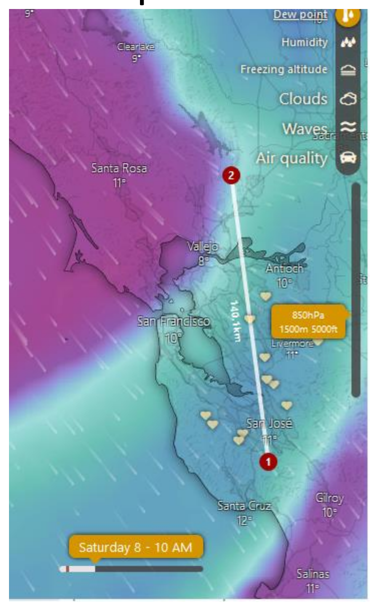
Tool: www.windy.com

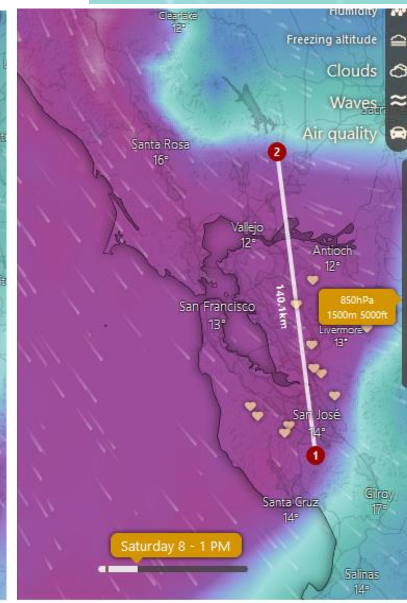
Dew Point forecasts, Fri 1 pm thru Sat 4 pm

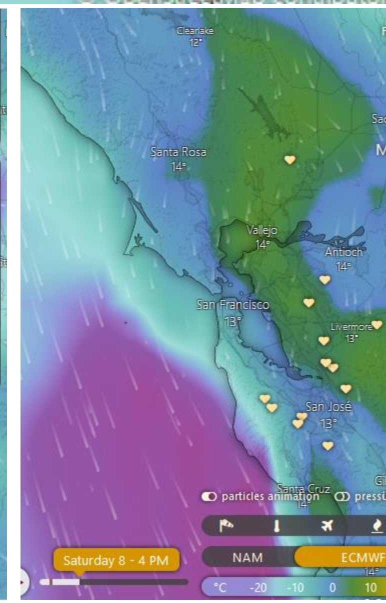












Fri 1300 | Sat 0400 | Sat 1000 | **Sat 1300 (wow!)** | Sat 1600

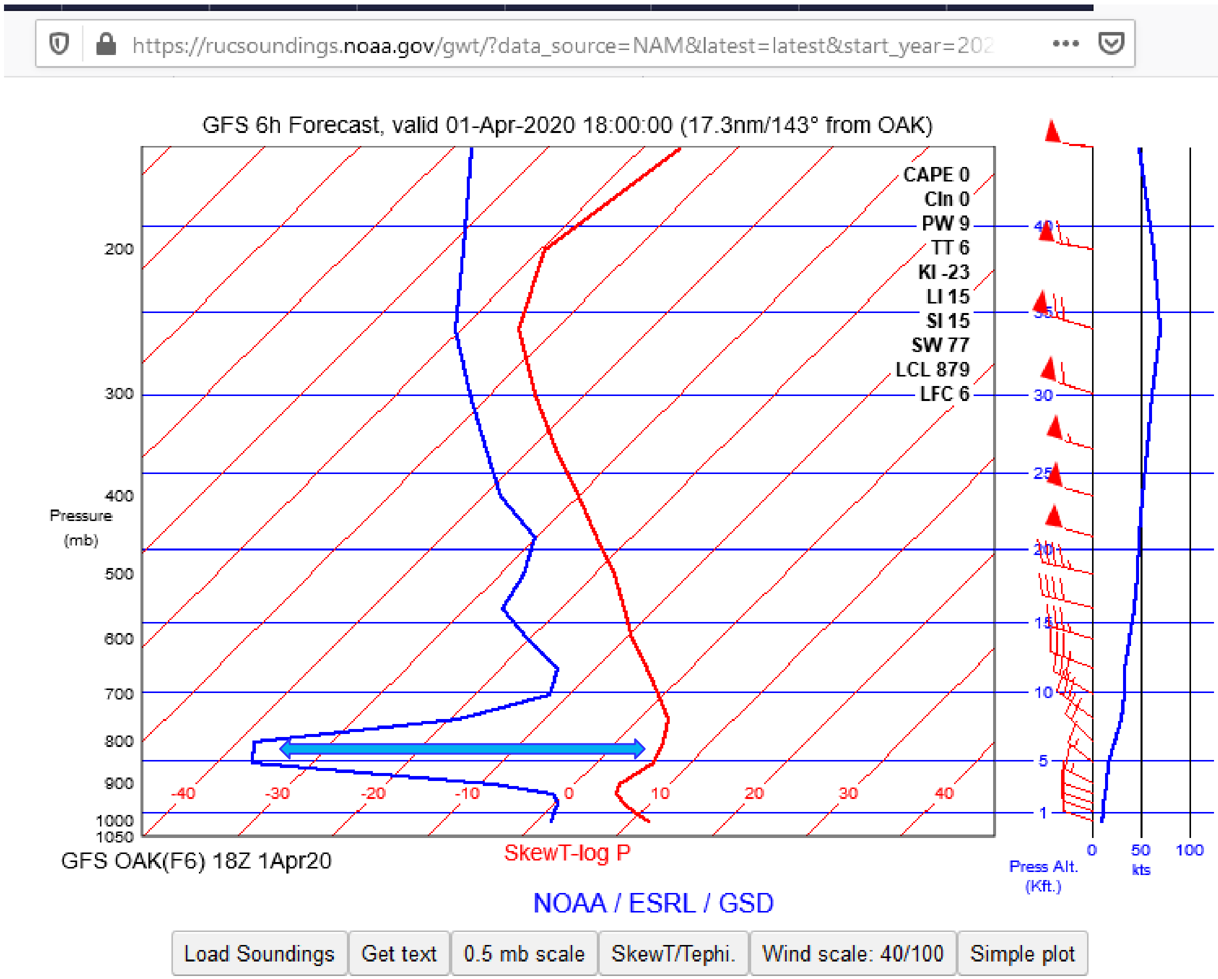
We want purple (close to -20C dew point) OVER THE ENTIRE PATH if possible…
Doesn’t happen very often or for very long

BTW: I use “custom colors” to set color scale to highlight the path’s max. usable dew pt.

Searching for the perfect wave in 4-D

moisture varies with elevation, too

Forecasts: https://rucsoundings.noaa.gov/
Archives: http://weather.uwyo.edu/upperair/sounding.html



"Skew-T" plots of dew pt (blue) and air temp (red)

vs

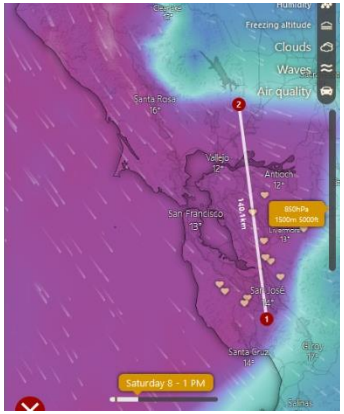
elevation (blue horiz lines, expressed in mbars of pressure)

Skewed red lines are constant temp/dew pt lines

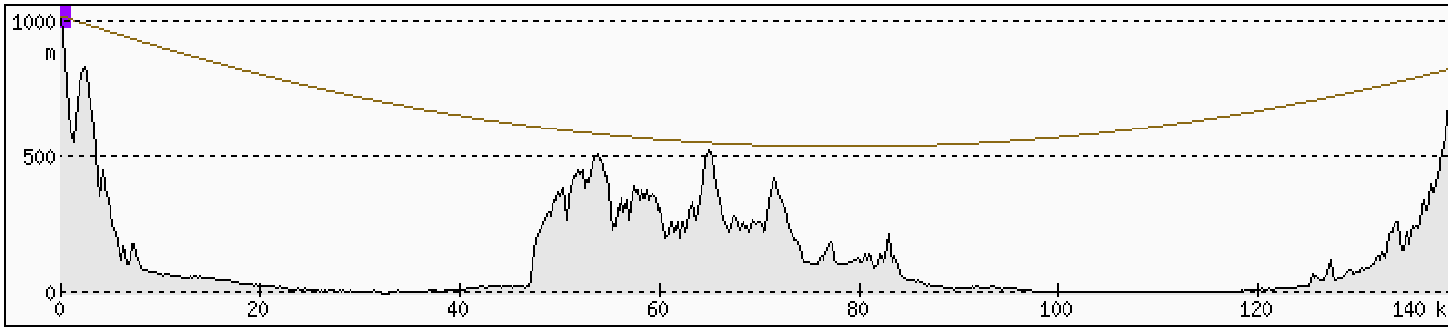
Wide gap between blue (dew pt) & red (air temp) lines shows a "dry duct" at 850-800 mbars (1500-2000m elevation)
(-37C dew / +5C temp / ~ 5% RH)

Searching for the perfect wave…

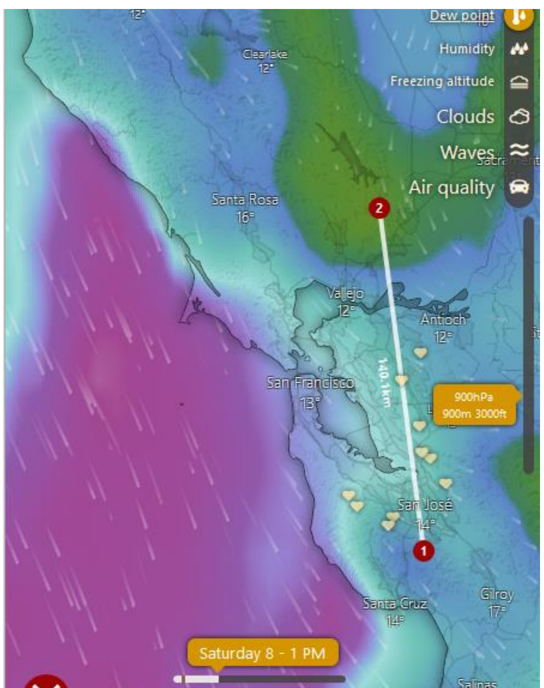
*Sat 1300 viewed at **correct altitudes along the path***



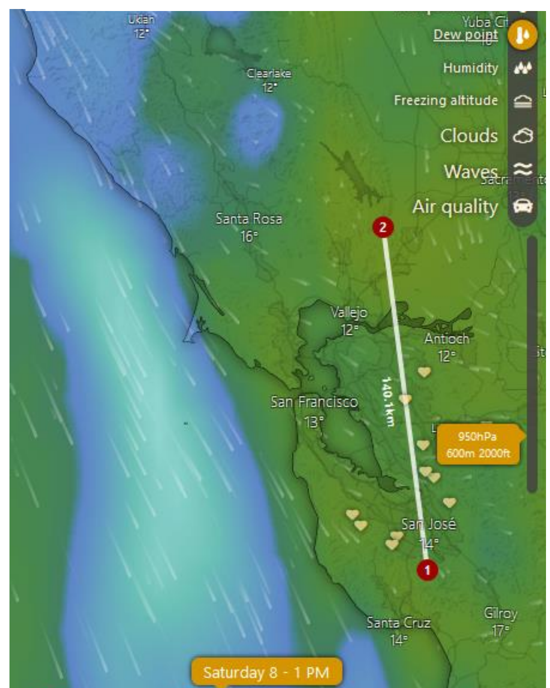
1500m (too high)



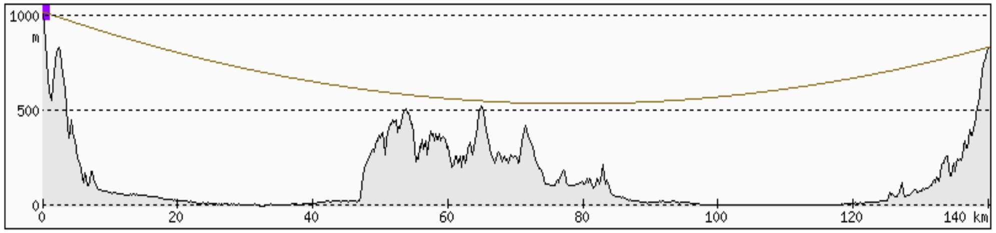
900m (Mt Um)



600m (midpoint 'droop')



750m (Mt Vaca)

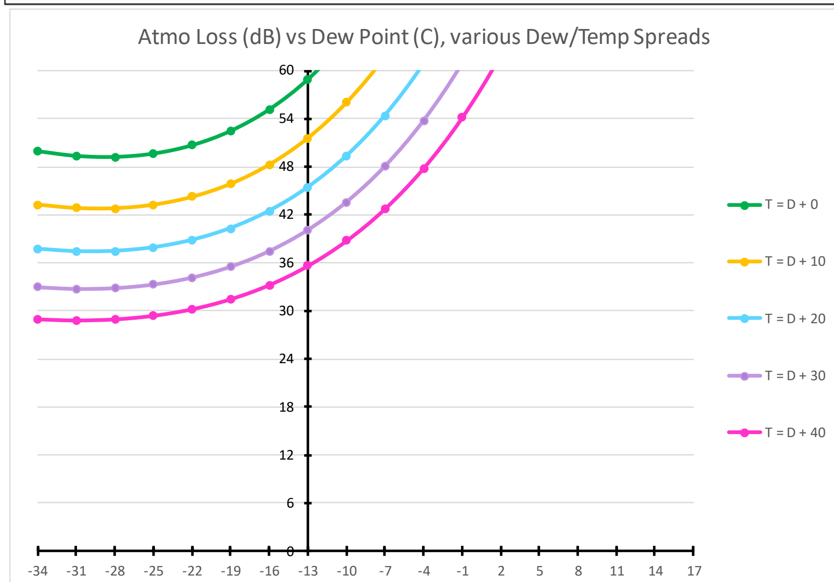


139 km QSO

(Umunhum - Vaca)

New World Record

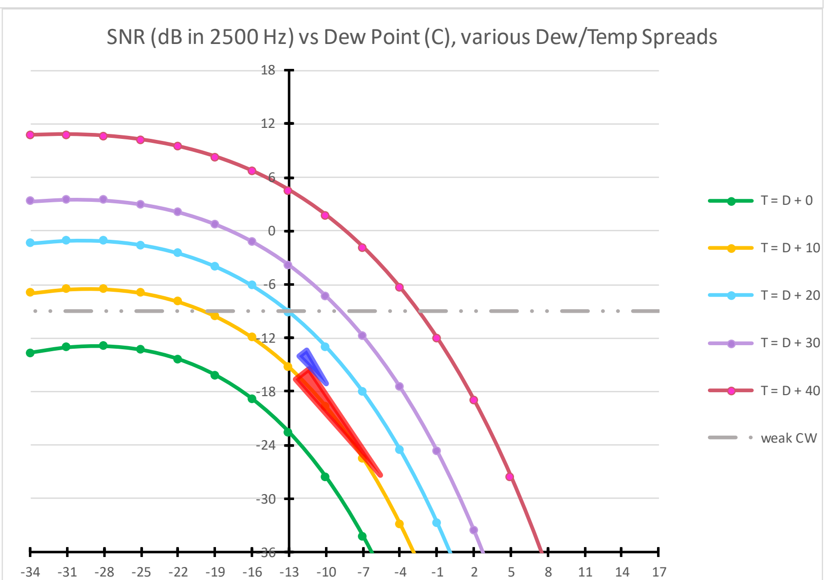
K6ML <-> KB6BA & N9JIM



Atmospheric Loss (in 1 “S” unit steps)
vs Dew Point (in 3 ^{o}C steps) for various Dew/Temp spreads (in 10 ^{o}C steps)

- 7.5 S units for -13 ^{o}C T_d & 20 ^{o}C spread
- Well over 10 S units when not dry
- FSPL goes up **5** dB (177 dB) from 80 km
- Atmospheric loss went up **21** to **>100** dB

- The weather is **THE** critical factor…
- First attempt failed
  - ✓ Midpoint much worse than end pts
- About 2 weeks later, better WX = success
  - ✓ Over 8 S units of atmos. Loss
  - ✓ Much better midpoint condx



SNR (dB), again assuming a 213 dB system

- Very dry days are “weak CW” copy…
- Even if we can get dry endpoints,
  Wet points along the path can sink us