Analysis of some tropospheric openings on 47GHz and 24GHz

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DX are always good opportunities to investigate propagation phenomena, especially when they are exceptional. During November 2006 great DX have been worked on 47GHz and 24GHz in Europe. In France F6BVA and F6ETU made a 300km contact on 47GHz during November 11th, and F6DWG had a QSO with HB9AMH over 450km on 24GHz. These two QSOs are some of the numerous other great DX achieved during this period. They will be used as examples here.
In this article air masses are investigated to highlight the tropospheric conditions that were responsible for these intense openings.
Observation and post-analysis is necessary if we want to predict more accurately these openings but it represents a huge work and it requires a high level of knowledge to understand what kind of meteorological conditions could lead to such unusual air masses configurations.
This article consists of a general discussion on tropospheric propagation followed by detailed analysis of the two QSO on 24GHz and 47GHz.

General discussion on the tropospheric propagation

Effect of the refractivity of the air

Abnormal change in refractive index with height leads to abnormal bending of radiowaves towards the ground. The radius of curvature is given by:

$$rad\_curv^{-1} = \frac{dN}{dh}$$

with :
rad_curve : radius of curvature in meters
N : refractivity index of the air
h : eight in meters

The curvature is always directed towards the increasing of refractivity e.g. in the same direction as the gradient of N.

The radius of curvature of the earth is equal to 6378 km. Therefore if the refractivity gradient is 1/6378 = 157 x 10^{-6} km^{-1} the radiowave will follow the curvature of the earth. If it exceeds this value, radiowaves are bent down towards the earth and then becoming trapped near the surface and can propagate over very long distances.

According to atmospheric science, the refractive index depends mainly on the atmospheric pressure, the temperature and the water vapour concentration in the air.
The most important influencing factor is water vapour (humidity). A warm dry air mass on top of a cooler humid air mass is the best configuration for creating strong inversion.

In our analysis we need to calculate the refractivity of the air from sounding data. In order to make figures easy we define the “refractivity” $N = (n-1).10^6$, with n the refractive index. The value of the refractive index of air is very close to unity, typically 1.0003.
The formula used to calculate N is:

$$N = 77{,}6.\frac{P}{T} + 3{,}73.10^5.\frac{e.f}{T^2} = N_{dry} + N_{wet}$$

with:
- T : Temperature in Kelvin
- P : Pressure in hPa
- f : relative humidity between 0 and 1 (or H/100)
- e : pressure of saturating water vapour

e is calculated using MAGNUS formula:

$$e = 6{,}10.10^{(7{,}448.t/(234{,}7+t))}$$

with t : temperature of the air in °C.

“e.f” is the partial water vapour in the air.

N is the sum of two terms, the “dry term” N_{dry} which covers dry gases, mainly Nitrogen and Oxygen and the “wet term” N_{wet} governed by water vapour.

In standard conditions, N decreases by 40 units per km in temperate regions. If this rate exceeds 157 units per km then radiowaves can be trapped between an inversion layer in the troposphere and the surface of the Earth or between layers in the troposphere depending on the refractivity profile. This is generally called a duct and the wave propagates the same way as in a waveguide. Propagation is no longer troposcatter and corresponding path loss increases directly with range rather than with range squared, resulting in a much lower path loss and very high signal levels for long ranges (>800 km).
It has been observed that during ducting, inversion layers can be especially sharp and well localised along the refractivity profile.

Very often refractive gradient is greater than “standard” gradient but does not exceed 157 units/km. This is called tropospheric enhancement but not ducting. Tropospheric enhancement is due to a slight and spread inversion caused by the ground that radiates heat and then keeps the upper air warm whereas the air near the ground cools. It’s common during the night and early morning, causing enhancement of the signal strength but not long range DX (it just makes the radio horizon farter and then enhances tropo scatter).

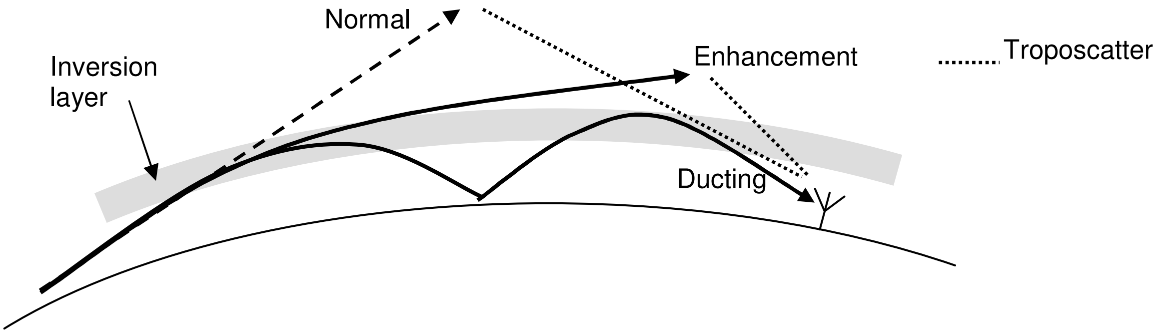

Figure 1 : Tropo enhancement and ducting

In opposite to temperature and pressure, humidity is very variable over meteorological conditions. That's the reason why N_{wet} is the major varying part of N.

Effect of the air absorption

Above 10 GHz air absorption becomes very significant, especially when paths are getting longer (>200 km).

Let's consider a standard wet air at ground level : 15°C, 1013 hPa and 60% humidity and a dry air with 15°C and 1013 hPa, we get the absorption values in Table 1.

Wet air (15°C, 1013 hPa, 60% humidity)				
	Oxygen + Dry air continuum absorption (dB/km)	**Water vapour absorption** (dB/km)	**Total air absorption** (dB/km)	**Absorption for a 100km path**
10 GHz	0,008	0,007	0,015	1,5
24 GHz	0,014	0,171	0,186	18,6
47 GHz	0,135	0,118	0,253	25,3
Dry air (15°C, 1013 hPa, 0% humidity)				
	Oxygen + Dry air continuum absorption (dB/km)	**Water vapour absorption** (dB/km)	**Total air absorption** (dB/km)	**Absorption for a 100km path**
10 GHz	0,008	0	0,008	0,8
24 GHz	0,014	0	0,014	1,4
47 GHz	0,135	0	0,135	13,5

Table 1: Absorption values of wet and dry air

Absorption is calculated in this article based on the formulas of the ITU-R recommendation P.676-6 "Attenuation by Atmospheric Gases". These formulas are to long (and boring!) to write them here. Accuracy is about 10% below 54 GHz.

For a 100 km path we observe a difference between wet and dry air of 0,7 dB at 10 GHz, 17 dB at 24 GHz and 12 dB at 47 GHz. It is obvious that for long paths, air absorption plays a significant role. Even though absorption decreases with altitude (because pressure is getting lower) it seems that dry air is needed for an opening to be successful above 10 GHz.

Getting tropospheric data

All over the world, and then over Europe, several stations performs atmospheric soundings twice a day. Balloons are used and during their ascension across the troposphere they send back to the stations valuable data. Soundings take place twice a day at 00H00 TU and 12H00 TU.

Archives are available in the public domain and can be easily downloaded on the Internet. A good site for retrieving sounding data is the site of the University of Wyoming:
http://weather.uwyo.edu/upperair/sounding.html
In France we have 6 stations covering the hexagon (F) and another station located in Corsica (TK). For a nice view of sounding profiles displayed on a map, go to:
http://www.infoclimat.fr/radiosondages/

300km+ QSO on 47GHz

This QSO took place between F6BVA/P and F6ETU/P on November 11th during the morning. Signals were booming at both sides.
F6BVA was located at the top of Mont Ventoux JN24PE at 1890m ASL.
F6ETU was located at Col de Paillère JN02XR at 2300m ASL. Both are micro watt class stations (100 uW) with 50dBi dishes and around -124 dBm sensitivity.

Both stations are always in line of sight from a radio path (not optical) and the Fresnel ellipsoid is not obstructed. The link margin can be calculated using the free space loss formula. In this case it gives 175 dB for space loss and a link margin of 39 dB without air loss.

Fortunately, a sounding station is located just inside the path of the QSO. Nimes-Courbessac station will then provide very valuable data for the analysis.
The map on figure 2 show the relative locations of the operators and the sounding station.

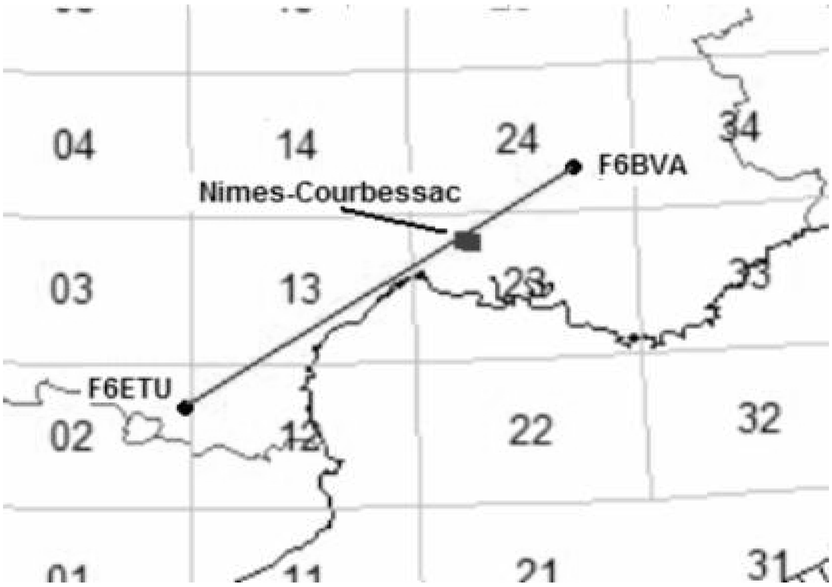

Figure 2 : 47 GHz QSO path

Table 2 is an example of downloaded text data.

Each row corresponds to a different sounding height. From each column we can read values for : pressure (« PRES »), temperature (« TEMP »), dew point temperature (« DWPT »), relative humidity (« RELH »), water vapour mixing ratio (g H2O/kg dry air) (« MIXR »), wind directions (from « DRCT » to « THTV »). Altitude (« HGHT ») is the corresponding eight above the see level (asl).

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    07645 LFME Nimes-Courbessac Observations at 12Z 11 Nov 2006
-----------------------------------------------------------------------------
   PRES   HGHT   TEMP   DWPT   RELH   MIXR   DRCT   SKNT   THTA   THTE   THTV
    hPa      m      C      C      %   g/kg    deg   knot      K      K      K
 1021.0     62   16.2   10.2     68   7.70    110      2  287.6  309.5  289.0
 1000.0    238   13.4    8.9     74   7.20    140      4  286.6  306.9  287.8
  996.0    272   13.0    8.7     75   7.13    146      4  286.5  306.6  287.7
  981.0    399   12.4    8.7     78   7.24    168      6  287.1  307.6  288.4
  952.0    650   11.0    2.0     54   4.67    213      8  288.2  301.7  289.0
  925.0    890    9.8    2.8     62   5.09    255     11  289.3  304.1  290.2
  914.0    989    9.3    2.9     64   5.20    270     12  289.8  304.9  290.7
  885.0   1256    8.0    3.3     72   5.51    279     15  291.1  307.2  292.1
  872.0   1378    8.0  -14.0     19   1.49    283     16  292.4  297.1  292.6
  850.0   1589    8.0  -24.0      8   0.65    290     18  294.5  296.7  294.6
  846.0   1628    8.0  -27.0      6   0.50    291     18  294.9  296.6  295.0
   …
```

Table 2 : Typical sounding data

Sounding analysis at 00H00 TU

Table 3 displays the sounding data and all the interesting values calculated: refractivity N with N_{dry} and N_{wet} terms, refractivity gradient and air absorption at 47 GHz. Path absorption is calculated for a constant altitude eight.
Figure 3 is the sounding profile with relative humidity and temperature. A very common one.
Figure 4 displays the air refractivity profile. The gradient and the profile both follow the standard -40 units/km rate.
Figure 5 is the air refractivity gradient profile. Values stay around -40 units/km (thin vertical line). Dashed line represents the -157 units/km limit, needed for the radiowave to be bent down towards the earth.

It is obvious that no tropo conditions are encountered at 00H00 TU. Since both stations are in line of sight due to their altitude, the radiowave propagates in straight line (within a 4/3 earth radius to be correct).

Figure 6 is the air absorption profile at 47 GHz. We can see a decreasing rate of around -30dB/km above 1000m. Air absorption is 50dB at 1500m and 70 dB at 250m. This leads to estimate roughly the air loss to 60dB.
The total link margin is 39 - 60 = - 21 dB. No copy!

Alt (m)	**H (%)**	**T (°C)**	**P (hPa)**	**Water vapour (g/m3)**	**N**	**Ns**	**Nh**	**Gradient (1/km)**	**Absorption water vapour**	**Absorption dry air**	**Total absorption**	**Absorption of path**
									dB/km	**dB/km**	**dB/km**	**dB**
62	80	6	1023	5,9	320,4	284,5	35,9	-	0,090	0,153	0,242	75
244	66	11	1000	6,7	313,4	273,2	40,1	-3,9E+01	0,105	0,140	0,245	76
286	62	12	995	6,7	310,9	270,9	40,0	-5,8E+01	0,105	0,138	0,242	75
526	48	14	967	5,9	296,3	261,5	34,8	-6,1E+01	0,090	0,128	0,218	67
774	54	13	939	6,2	291,7	254,8	36,9	-1,8E+01	0,096	0,122	0,217	67
900	58	13	925	6,7	290,7	251,0	39,7	-8,4E+00	0,104	0,118	0,222	69
1000	58	12	914	6,3	286,3	248,9	37,4	-4,4E+01	0,097	0,116	0,213	66
1576	38	10	854	3,6	255,9	234,2	21,8	-5,3E+01	0,051	0,103	0,155	48
1606	37	9	850	3,3	253,8	233,9	19,9	-6,9E+01	0,046	0,103	0,150	46
2386	2	6	776	0,1	216,7	215,8	0,9	-4,8E+01	0,002	0,088	0,090	28
2514	1	5	761	0,1	212,8	212,4	0,4	-3,0E+01	0,001	0,086	0,087	27
3179	1	2	701	0,1	198,2	197,8	0,3	-2,2E+01	0,001	0,075	0,075	23

Table 3 : Sounding data (00H00 TU)

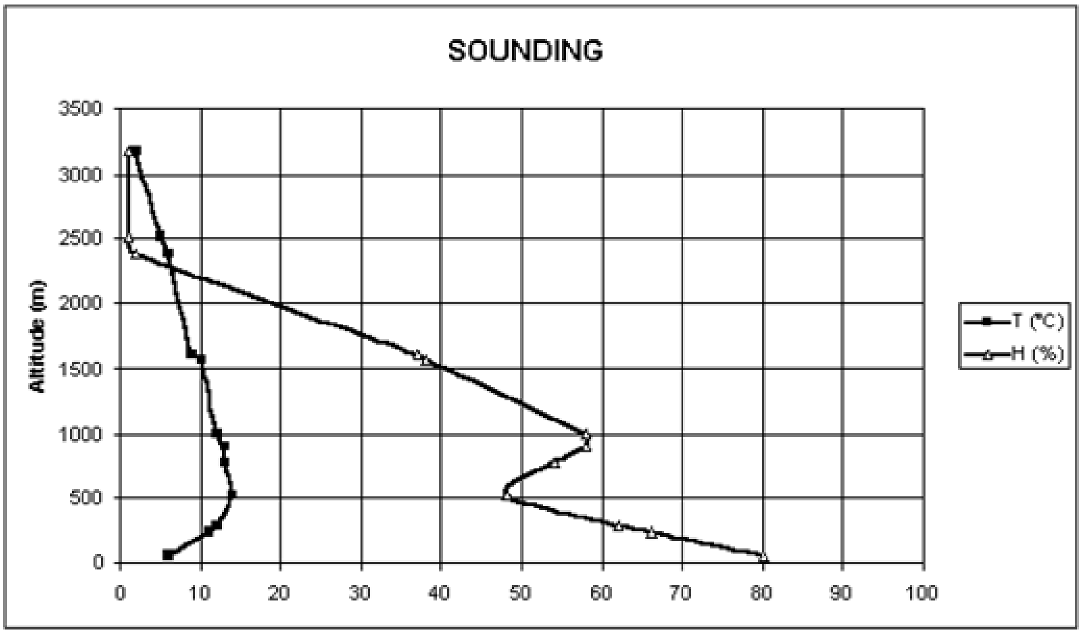


Figure 3 : Sounding profile (00H00 TU)

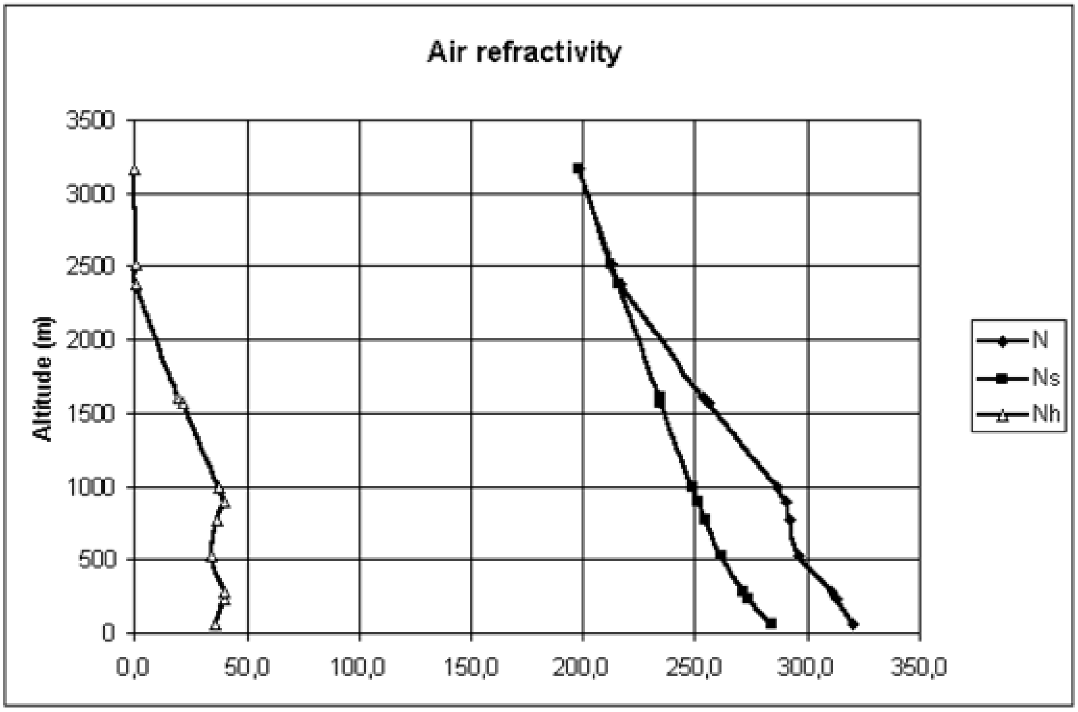


Figure 4 : Air refractivity profile (Ns = N_{dry} Nh=N_{wet}) (00H00 TU)

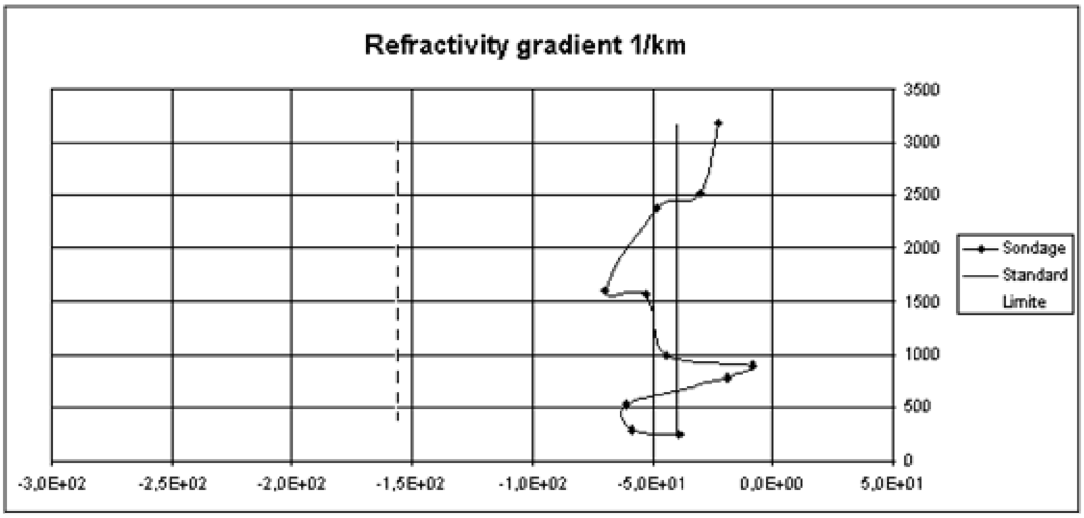


Figure 5 : Air refractivity gradient profile (00H00 TU)

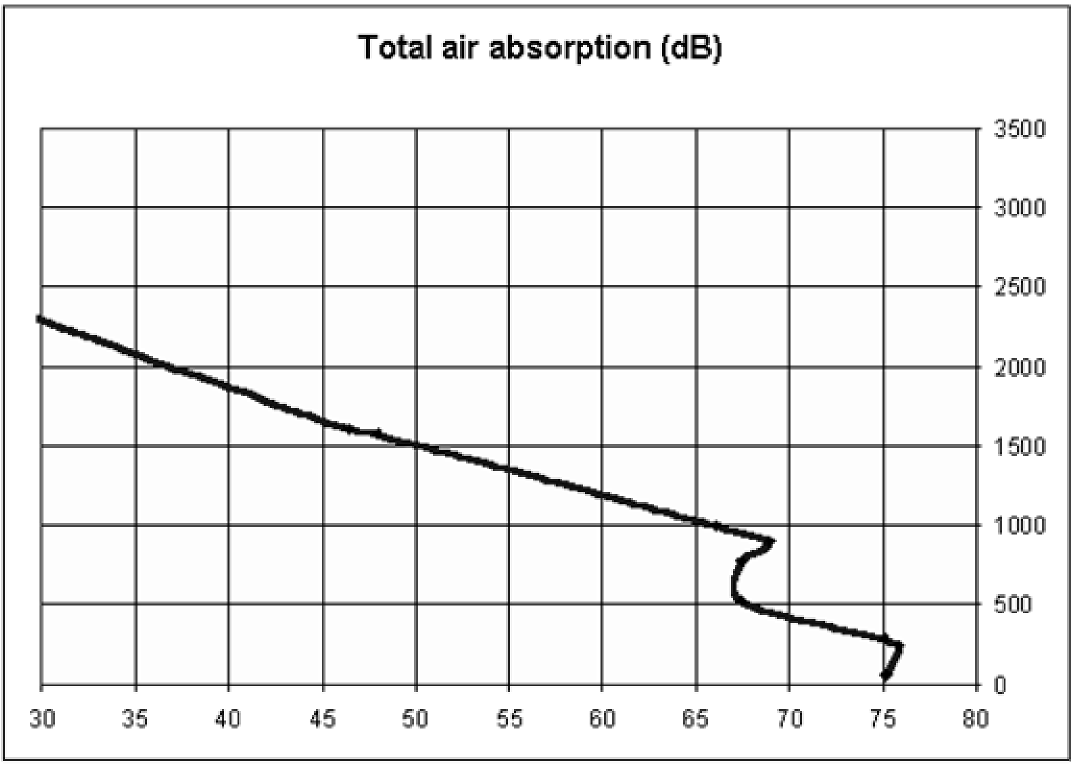


Figure 6 : Air absorption profile at 47 GHz (00H00 TU)

Sounding analysis at 12H00 TU

Data are collected and analysed exactly the same way.
Now it becomes clear that great conditions occurred at 12H00 TU.

Sounding profile of figure 7 shows a significant drop of 70% in relative humidity at 1500m. Note that temperature profile is not disturbed at all (no temperature inversion).

Refractivity profile (figure 8) is disturb by the N_{wet} term. N_{dry} is not disturbed at all.
We understand the big influence of N_{wet} variations on N variations even if N_{wet} represents only 15% of the total value of N.
Refractivity gradient (figure 9) shows a sharp increase at 1300m, peaking at -250 units/km, exceeding well the -175 units/km limit.

It becomes obvious that ducting condition has appeared at 12H00 TU with a sharp inversion at 1300m asl.

It is difficult to determine exactly the radiowave path associated with this inversion. We don't have other sounding data at other locations, then it is impossible to conclude on the exact path. Radiowave must have been bent all along this inversion layer without crossing the lower atmosphere otherwise absorption would have been to important. Remind that both stations are always in line of sight then only a significant decrease in air loss can be responsible for a successful QSO on 47 GHz.

Let's assume that the radiowave stayed at the same eight, along the path.
On figure 10 the absorption profile shows a significant decrease in air loss around 1500m. This would lead to a total absorption of 35dB. Compared to 00H00 TU this is a 25dB enhancement. The total link margin becomes 39 – 35 = + 4 dB. QSO is possible!

Alt (m)	**H (%)**	**T (°C)**	**P (hPa)**	**Water vapour (g/m3)**	**N**	**Ns**	**Nh**	**Gradient (1/km)**	**Absorption water vapour**	**Absorption dry air**	**Total absorption**	**Absorption of path**
62	68	16	1021	9,4	329,5	274,2	55,3	-	**dB/km**	**dB/km**	**dB/km**	**dB**
238	74	13	1000	8,5	322,0	271,3	50,6	-4,3E+01	0,140	0,138	0,278	86
272	75	13	996	8,7	321,6	270,2	51,3	-1,2E+01	0,143	0,137	0,279	87
399	78	12	981	8,5	317,4	267,1	50,3	-3,3E+01	0,139	0,134	0,272	84
650	54	11	952	5,5	293,0	260,1	32,8	-9,8E+01	0,083	0,127	0,210	65
890	62	10	925	5,9	289,1	253,6	35,5	-1,6E+01	0,090	0,121	0,211	66
989	64	9	914	5,7	286,0	251,5	34,5	-3,2E+01	0,087	0,119	0,206	64
1256	72	8	885	6,1	280,9	244,4	36,5	-1,9E+01	0,092	0,113	0,205	64
1378	***19***	***8***	***872***	***1,6***	***250,4***	***240,8***	***9,6***	***-2,5E+02***	***0,021***	***0,110***	***0,131***	***41***
1598	8	8	850	0,7	238,8	234,7	4,1	-5,3E+01	0,009	0,104	0,113	**35**
1628	6	8	846	0,5	236,7	233,6	3,0	-7,1E+01	0,006	0,103	0,110	**34**
1815	25	8	827	2,1	241,1	228,4	12,7	2,3E+01	0,028	0,099	0,127	39
2201	65	5,4	789	4,6	248,0	219,9	28,1	1,8E+01	0,067	0,092	0,159	49
2368	65	4	773	4,2	242,2	216,6	25,7	-3,4E+01	0,061	0,089	0,150	46
2635	65	2,4	748	3,8	234,0	210,8	23,2	-3,1E+01	0,054	0,085	0,138	43
3169	64	-1	700	2,9	218,0	199,7	18,3	-3,0E+01	0,041	0,076	0,117	36
3781	63	-4	648	2,3	201,6	186,9	14,7	-2,7E+01	0,032	0,067	0,099	31

Table 4 : Sounding data (12H00 TU)

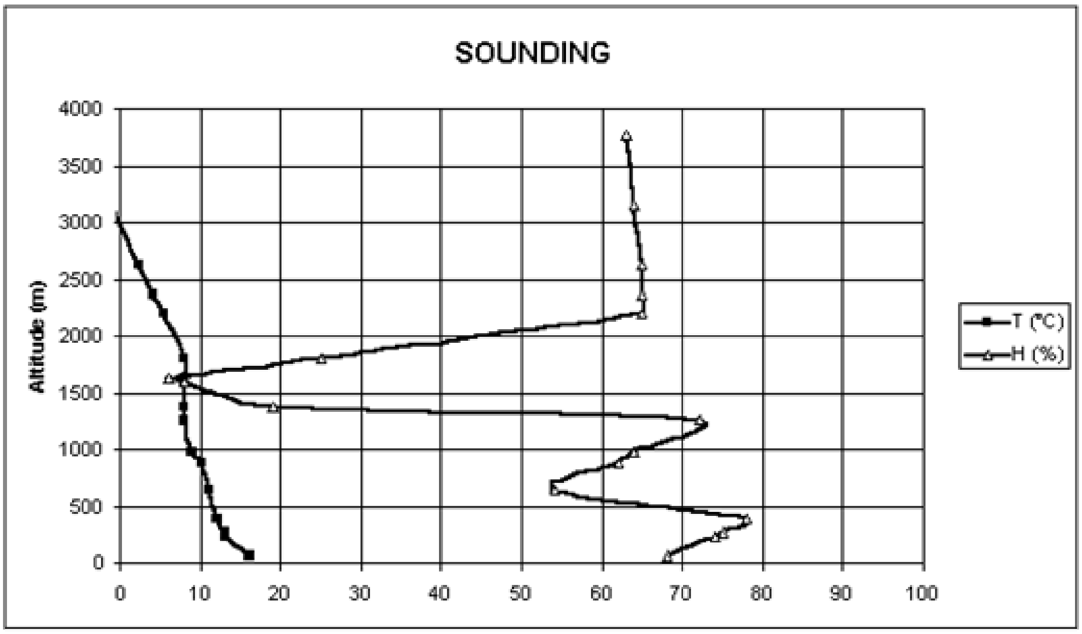


Figure 7 : Sounding profile (12H00 TU)

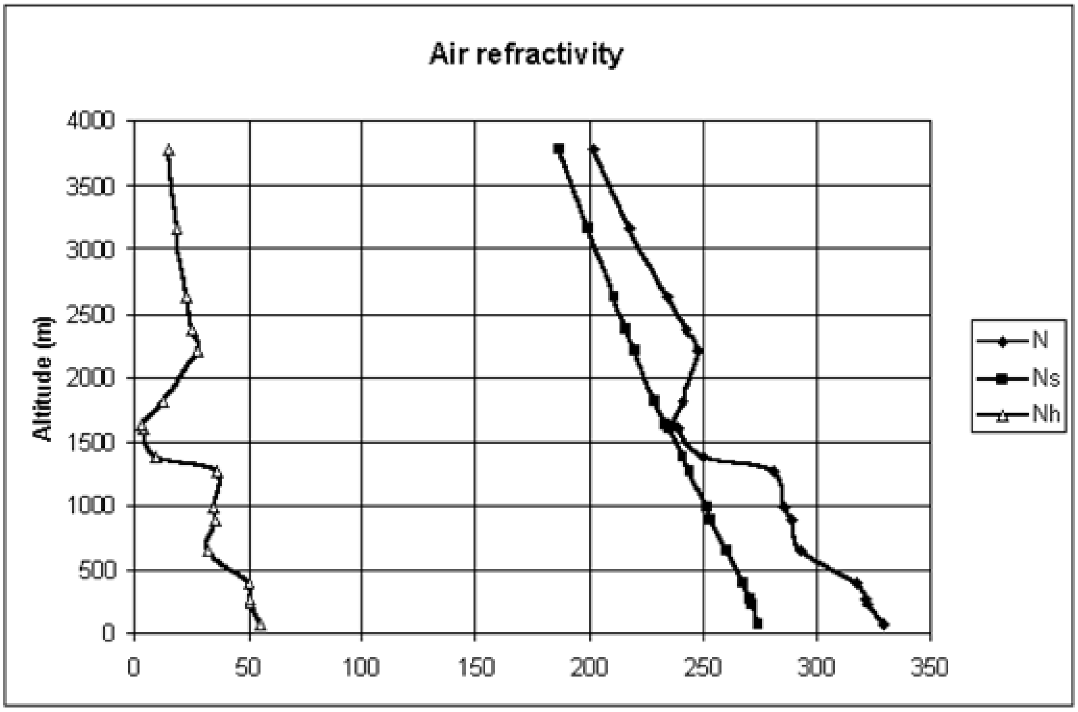


Figure 8 : Air refractivity profile (Ns = N_{dry} Nh=N_{wet}) (12H00 TU)

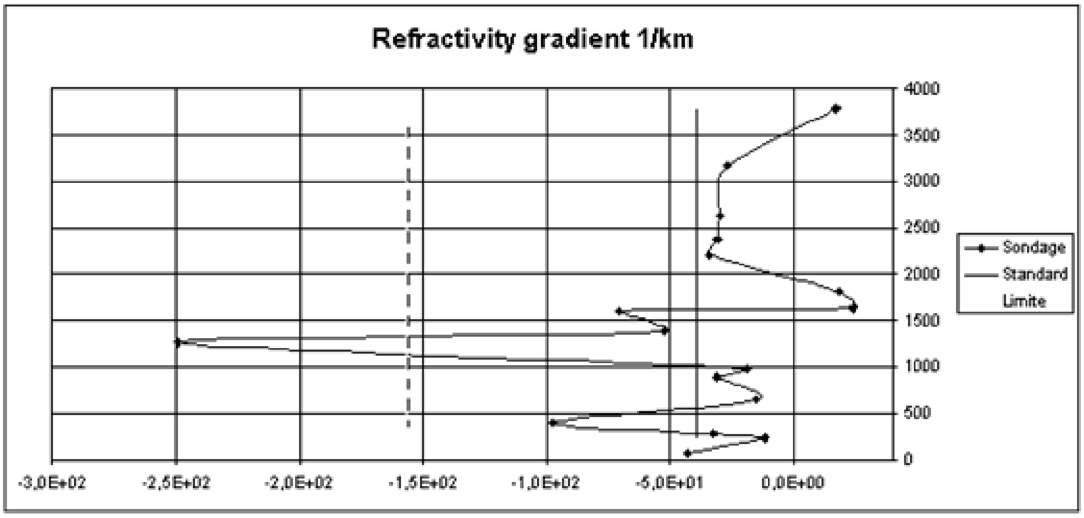


Figure 9 : Air refractivity gradient profile (12H00 TU)

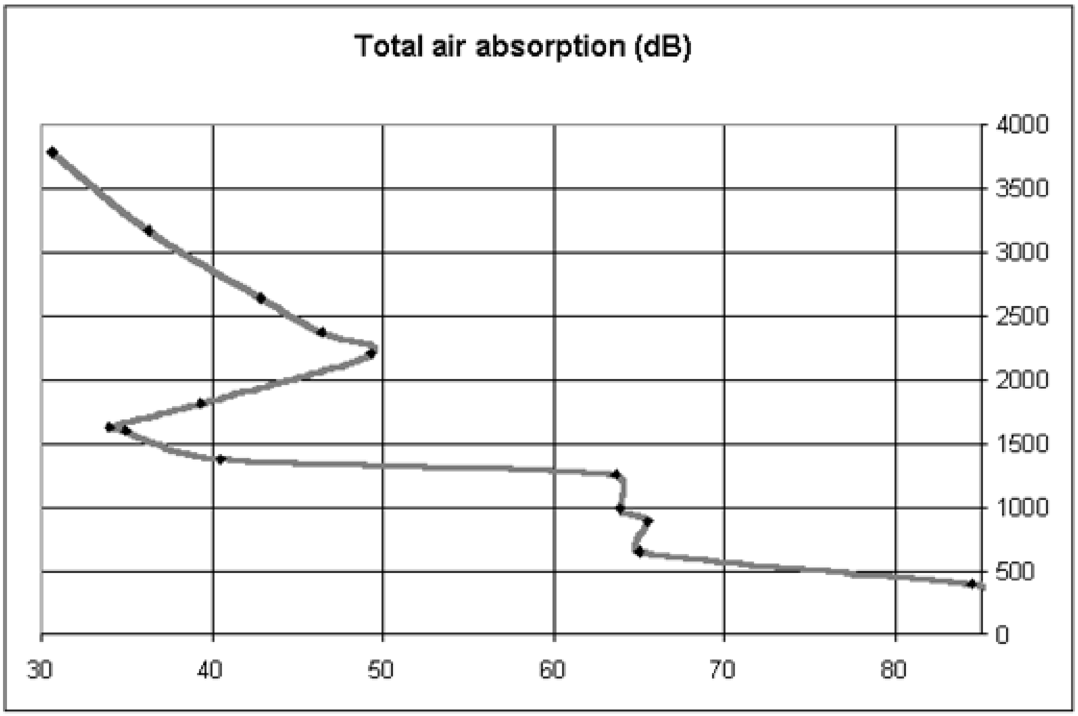


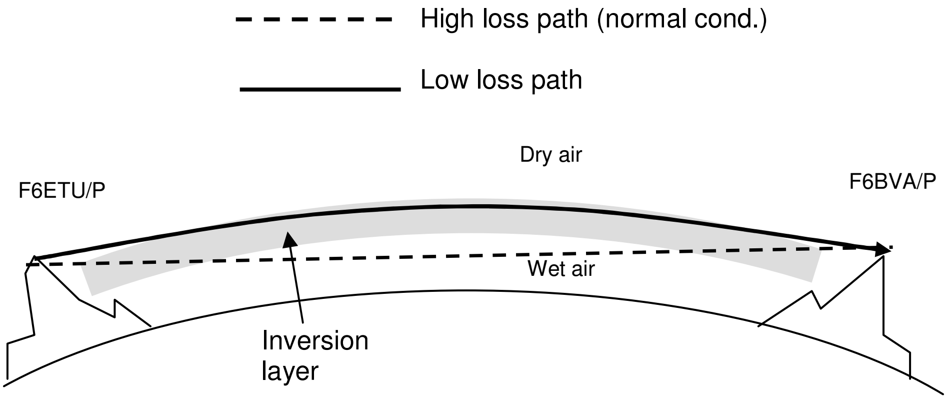
Figure 10 : Air absorption profile at 47 GHz (12H00 TU)

We can extrapolate between 00H00 TU and 12H00 TU and conclude that an inversion has developed during the morning at about 1500m asl. This inversion is the consequence of a dry air layer above a wet air mass. This configuration has leaded to:

- a bending of the radiowave along the path
- a significant enhancement in overall path loss because of smaller absorption at 47 GHz of the dry air

It is impossible to affirm that such configuration has remained exactly the same all along the path, but a very good interpretation is that this inversion helped the radiowave traveling into a dry low loss layer. As a consequence great enhancement of the signal has been experienced.

Note that due to their high altitude, the inversion layer stayed “below” the two stations, then the radiowaves didn’t cross the layer and stay entirely in the dry low loss air.



F6ETU/P – F6BVA/P DX radio path

450km+ QSO on 24GHz

Another great DX have been worked on November 6th and 7th on 10, 24 and 47 GHz.
Let's have a look on the DX QSO between F6DWG/P (JN19AJ) and HB9AMH/P (JN37OE): a little more than 450 km have been achieved on 24 GHz. See map on Figure 11.
The same analysis is done than before, except that frequency is now 24 GHz. Refractivity gradient criteria is the same but air loss is now considered at 24 GHz. See Table 1 for attenuation differences compared to 47 GHz.
The atmospheric, refractivity and total attenuation (for a 450km path length) profiles at Trappes (JN18AS) location, near F6DWG/P QTH, are displayed on Figure 12, 13, 14 and 15. We consider the 00H00 TU sounding data of November 7th (close to the DX QSO time).

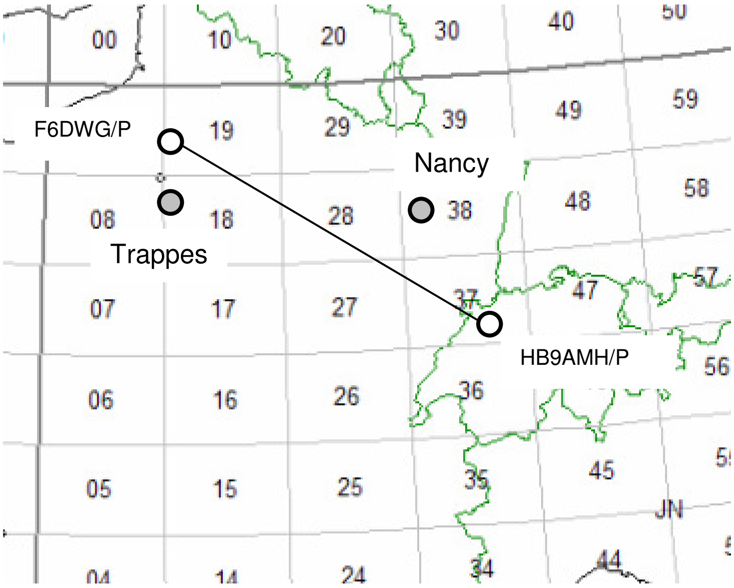


Figure 11 : Locations of DX stations and atmospheric sounding stations

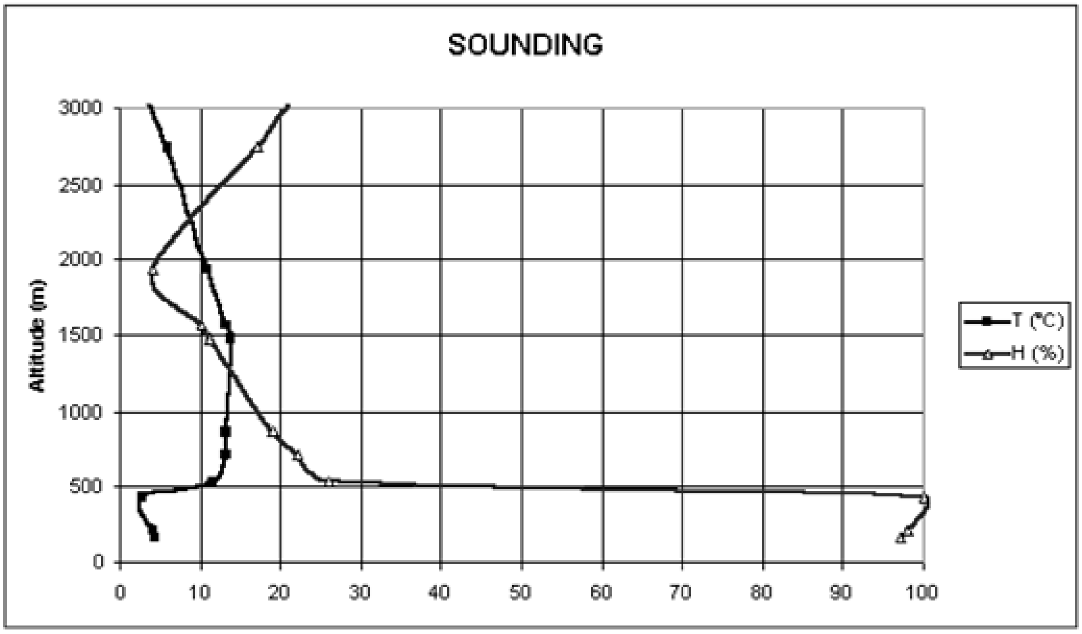


Figure 12 : Sounding profile, Trappes (00H00 TU)

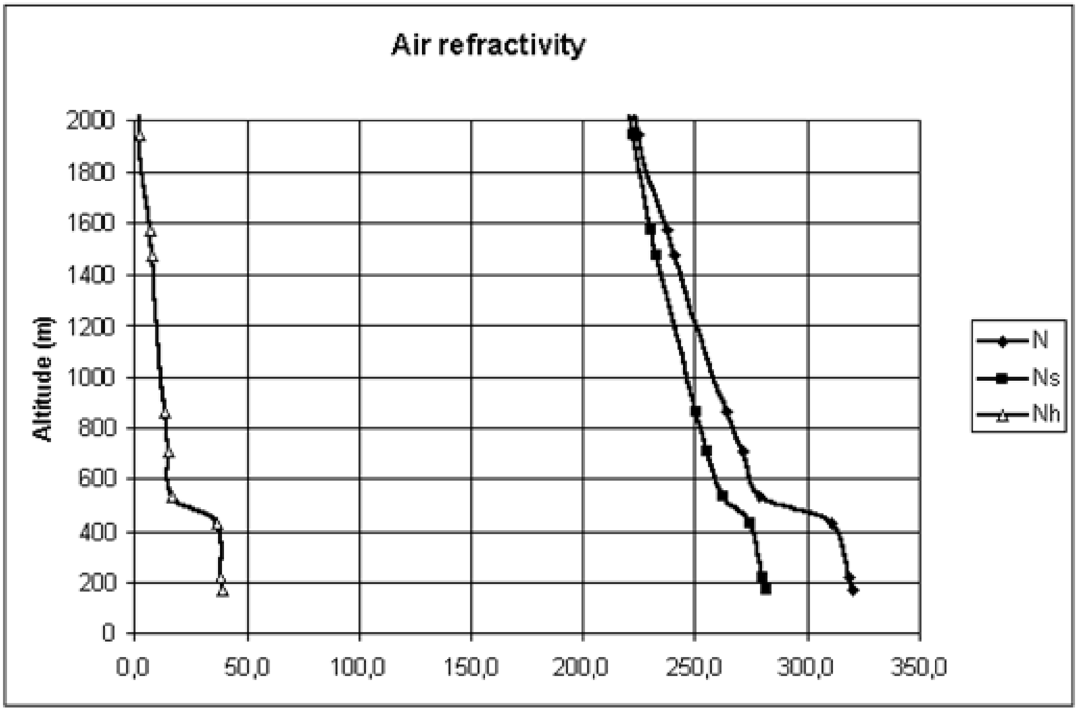


Figure 13 : Air refractivity profile (Ns = N_{dry} Nh=N_{wet}), Trappes (00H00 TU)

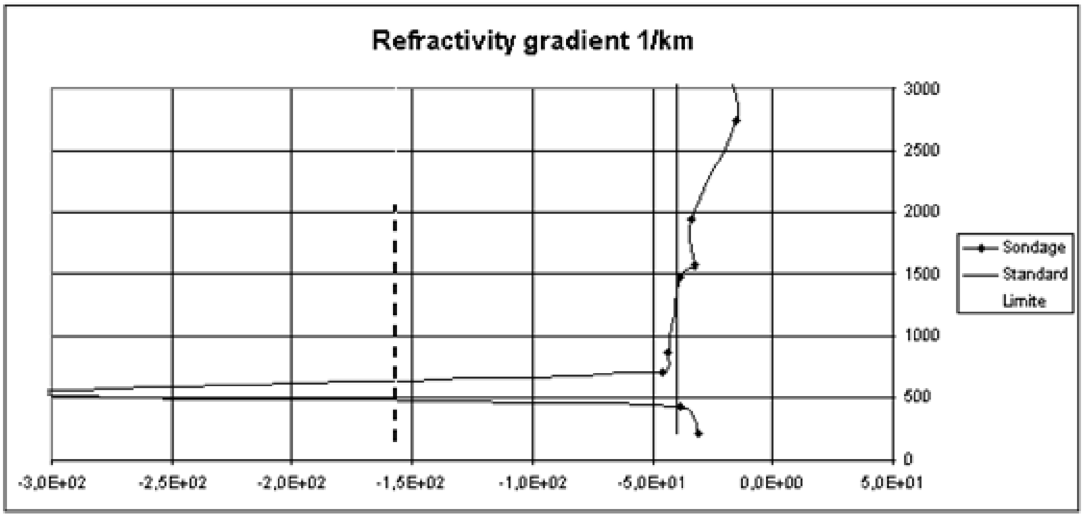


Figure 14 : Air refractivity gradient profile, Trappes (00H00 TU)

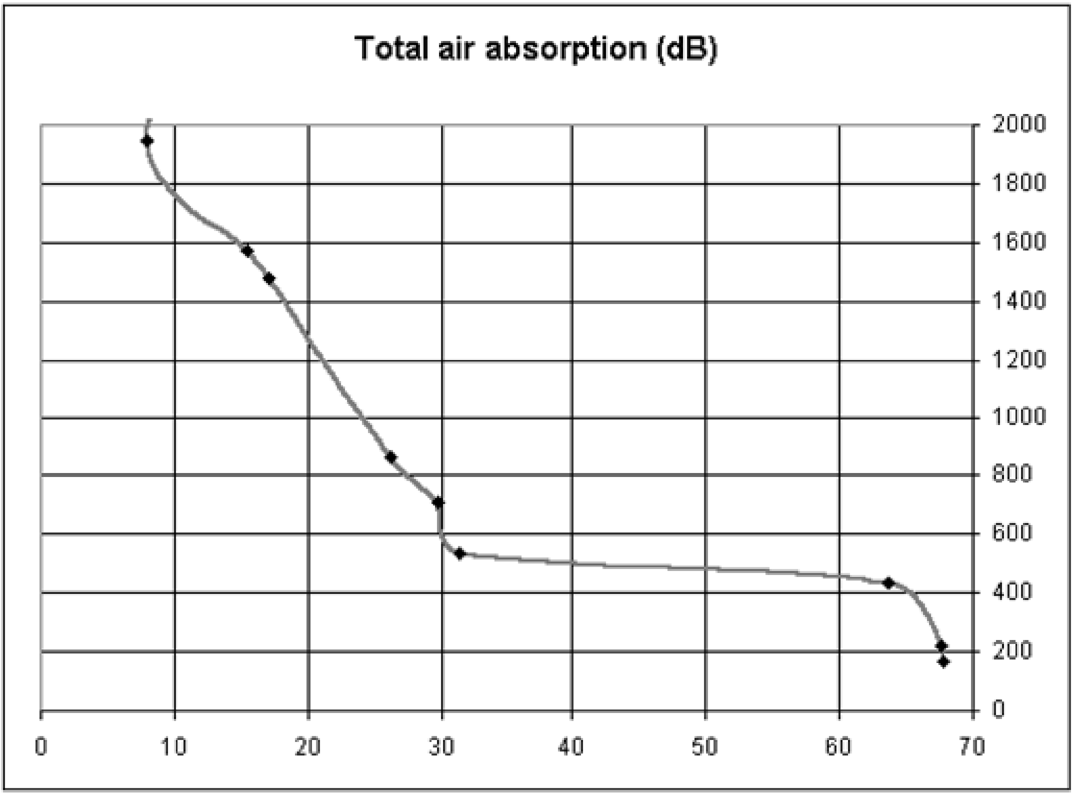


Figure 15 : Air absorption profile at 24 GHz, Trappes (00H00 TU)

Sounding and refractivity gradient profiles are impressive. The inversion is very strong and sharp around 500m asl, much lower than in the previous analysis (1300 m). Note that a temperature inversion is present at this altitude.
Total air loss decreases sharply at 500m from 65 dB to 30 dB. This is a very significant 35 dB improvement of the total path loss.

Again we can strongly assume that the radiowaves have been guided along the inversion boundary in a kind of low loss conduit.

Sounding data from Nancy location (JN38CQ) shows exactly the same profiles with an inversion slightly higher at 600m asl. Obviously conditions were very good in the east direction from Trappes. This explains other DX QSO during the same night on 10 GHz between F and OK stations.

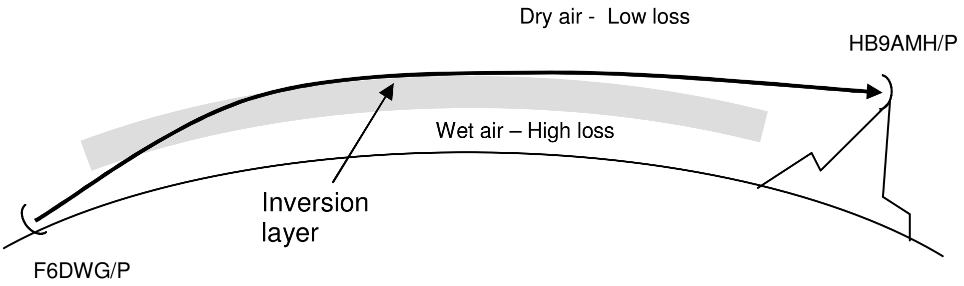


Figure 16 : Proposed radio path for F6DWG/P – HB9AMH/P DX

Propagation into the “Inversion” layer

In fact, an inversion layer is not “binary” even if it is actually very sharp as shown on the sounding profiles. Such an inversion is a transition between two very different air masses, a very wet one and a very dry one in our case. Temperature profile across the transition can also be abnormal (see Figure 12), this is often called “temperature inversion”.
In fact, across the transition layer, refractivity gradient and air attenuation is smoother than the results of our calculations (Table 1 and Figure 9). This is the result of the lack of intermediate values in sounding data.
Along the radio path, the radiowave is bended progressively and the following air absorption decreases progressively as long as the wave reaches the top part of the transition layer. Therefore, the longer is the QSO path, the longer the radiowaves stay in the transition layer and the longer is the low loss path and the greatest is the relative signal enhancement.

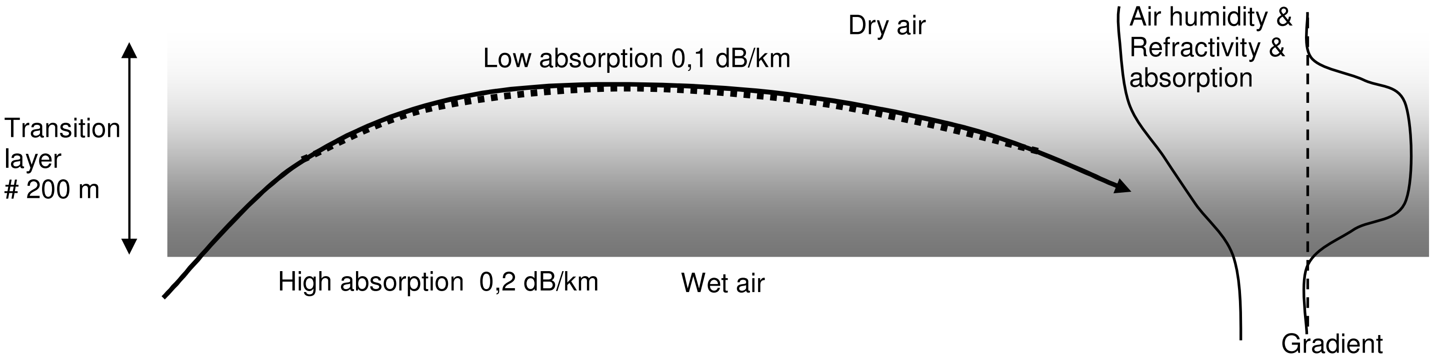


Figure 17 : Propagation across a transition layer

Some sounding stations provide very accurate sounding data and we can observe in theses profiles that the transition layer can be not smooth at all and that very numerous thin sub-layers are present. This is another subject of study, especially relevant for microwaves because such sub layers could lead to sub ducting for microwave wavelengths. The explanation of the process leading to such thin layering is very interesting but not the subject of this article.

In our calculation of the total air absorption (Figure 10) we have made the assumption that the radiowave crossed the transition layer at a constant altitude and that the altitude of the transition was constant. These approximations are pertinent for mid range QSO, say 300/400 km. For very long range QSO it may not be the case (with, in some cases, an extra reflection on the ground).

Conclusion

Compared to “classical” analysis on 144 MHz or 432 MHz, we see that air loss is an essential parameter for microwaves above 10 GHz. In many cases, the well known “temperature inversion” is not the critical parameter and inversion is in fact due to a “humidity inversion”. In conjunction with temperature inversion it leads to the best conditions.

The aim of this article was to quantify the role of air absorption even if calculating accurately the total air loss along a radio path would require knowing the exact radiowave path and also the exact absorption loss of the air along this path. This seems nearly impossible since atmospheric data are collected by a small number of soundings stations. Anyway, these two analyses of tropo DX prove the great variability of the total air loss along the pass that could lead to very significant signal enhancement by ten’s of dBs. Many microwaves DX could have not been possible without such air loss enhancement.
This article speculates also on the way radiowaves travels in the upper atmosphere and the first case study shows that radiowaves must have been guided into a low loss air mass otherwise, even with guiding, the QSO would have not been possible. In the second case it is not so clear if only guiding would have been enough to make this QSO possible. Anyway the same air absorption profile was encountered.

For further studies and, more especially, if we want to predict such microwaves openings we must define a model of the propagation mechanism. This task requires:

- more intermediate values on sounding data to get a more accurate refractivity profile and then to conclude on the exact radiowave path along the transition layers
- more DX case studies to correlate between air loss profile and DX
- due two the sometimes low transition layer height, other analyses of DX QSO with stations located at various altitude

Good DX!

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References for further readings:

[1] Very interesting articles can be found on DF5AI web site http://df5ai.net
[2] Sounding data from the University of Wyoming: http://weather.uwyo.edu/upperair/sounding.html
[3] Sounding data map for France: http://www.infoclimat.fr/radiosondages/
[4] http://www.mike-willis.com/Tutorial/refraction.htm . You can download here an air loss calculator: “GasLoss.exe”
[5] QSO database : EA6VQ http://www.vhfdx.net/
[6] F4BUC web site (in French): http://f4buc.chez-alice.fr
[7] ITU-R recommendation P.676-6 "Attenuation by Atmospheric Gases"