Atmospheric Models For Over-Ocean Propagation Loss

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Introduction

Air-to-surface radio links differ from typical satellite communications links in that the path elevation angles are lower, often 2 – 5 degrees, and so have a longer extent through the atmosphere. When signal frequencies exceed 10 GHz, propagation loss due to absorption by atmospheric gases become a significant link budget term. Losses over the ocean are even higher than over-land losses, due to increased humidity. Finally, when high reliability is desired, the log-normal assumption used to esimate required power margins from the loss mean and standard deviation is not accurate.

A set of atmospheric loss models has been developed from radiosonde profiles collected along the Atlantic coast of the United States, in order to accurately estimate high-reliability SHF/EHF air-to-surface radio link performance in a maritime environment, Data was collected at three locations approximately spanning the East Coast of CONUS: Chatham MA, Wallops Island VA, and Key West, FL. Weather station locations and identifiers are listed in Table 1.

The large quantity of historical radiosonde data available for those locations was used to identify radiosonde profiles that occur with specified probabilities. Those profiles were used to predict required link performance to achieve high reliability at different locations and times of year.

Data Acquisition

Radiosonde balloons are launched daily at the selected locations, and measure temperature, dew point temperature, and air pressure as they ascend. Radiosondes are ordinarily launched twice a day, nominally at midnight and noon UTC, which is 7 AM and 7 PM EST (8 AM and 8 PM EDT). Actual launch time is usually less than an hour before nominal launch time.

Radiosonde data is availablel on the internet at http:///esrl/.noaa.gov/raobs, for dates listed in [1]. The data format is described in [2,3,4]. The models presented here are based on all available radiosonde data files from the years 2004 – 2013. Text files containing radiosonde data for one month of one year were downloaded and converted to matlab matrices, then processed as follows:

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1) Unusable or undesirable lines were deleted, e.g. lines with missing measurements, or multiple copies of a single line.
2) Altitude measurements were converted from geopotential1[2] altitude to geometric altitude [5].
3) Water vapor partial pressure was calculated at each altitude from temperature, dew point temperature, and air pressure [6].
4) Water vapor density was calculated from water vapor partial pressure and temperature [7].
5) Data was interpolated to a set of consistent and more closely spaced altitudes

Table 1. Weather Stations

Location	WMO Number	Station Idendtifier	Latitude	Longitude	Altitude
Chatham, Massachusetts	74494	CHH	41.67°	-69.97°	16 m
Wallops Island, Virginia	72402	WAL	37.85°	-75.48°	3 m
Key West, Florida	72201	EYW	24.55°	-81.75°	1 m

Propagation Loss Calculation

The analysis used assumes weather data are constant inside a set of nested spherical shells, with shell edges at altitudes recommended in [8]. In step (5) above, data was interpolated to the mid-point of each shell. Using weather data, the index of refraction, or equivalently complex refractivity can be found in each atmosphere shell. The real part of the index of refraction determines how the radio path bends at shell boundaries, and is easily found to the necessary accuracy [9]. The imaginary part of refractivity determines atmospheric absorption, and must be more carefully approximated. Liebe's approximation [10], which is good for frequencies below 100 GHz, was used. It accounts for absorption by water vapor and oxygen. Water vapor has a resonant line at 22.2 GHz and dominates loss in the lower end of the band, oxygen has a series of resonant lines around 60 GHz, and makes a significant loss contribution at higher frequencies. The version of Liebe's approximation used is that in [8].

Path length was found using a ray-tracing model, as in [8]. Starting at ground level, the angle at which an uplink path entered a new shell was found from the angle at which it left the lower shell and the shell indices of refraction. The path was traced upward until it reached the desired altitude, and the ground range was found from the change in central angle subtended by the path.

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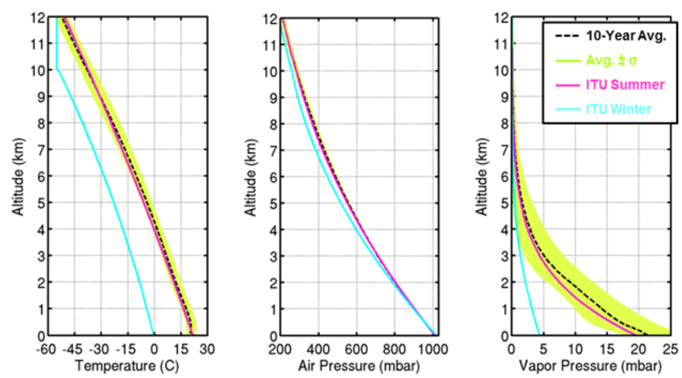
[2] Geopotential altitude is defined by a surface of constant gravitational potential energy, and does not equal geometric altitude. At 20 km altitude, the difference is approximately 120 m [5].

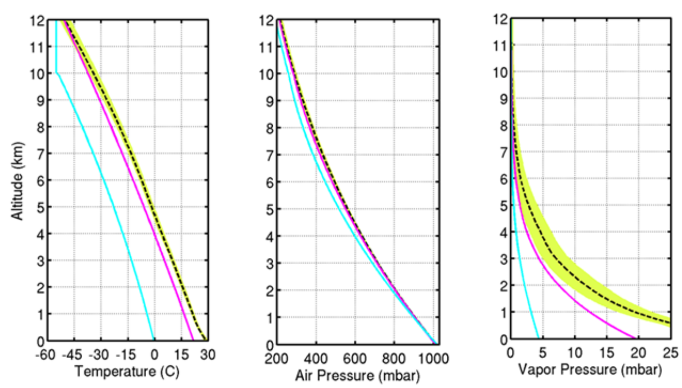
Gas absorption along the path was found as the summed product of path length through each shell, and the specific attenuation (dB/km) in each shell [8]. Specific attenuation is a simple function of the imagionary refractivity [8,10].

Atmosphere Characterization

Ten years of data were collected and analyzed for each location. Data means and standard deviations at each altitude were calculated. Figure 1 shows plots of parameter means and standard deviations at Chatham and Key West for July.The ITU mid-latitude standard atmospheres [11] are also plotted. The region between μ±σ is colored light green. Mean temperature at Chatham in July falls close to the ITU summer model, slightly below at the surface, and slightly above everywhere else. The Key West mean temperature is more than one standard deviation above the ITU summer model at all altitudes. Air pressure variance at both locations is small compared to the change in air pressure with altitude, and the air pressure green region is mostly concealed behind the ITU summer model line. Mean water vapor



a. Chatham, MA



b. Key West, FL

Figure 1. Weather statistics for July, from radiosonde data from 2004 – 2013.

parital pressure exceeds the ITU Summer model by less than one standard deviation at Chatham, and by several times the standard deviation at Key West. Wallops Island results fall between Chatham and Key West.

Converting the large quantity of weather data to propagation loss, then collecting loss statistics is a time consuming process. Furthermore, atmosphere loss margins for high reliability links calculated from those statistics under the assumption loss is log-normally distributed will produce innacurate results. As an alternative, all of the radiosonde data collects for a given month over ten years have been ranked according to their approximate severity of propagation loss. Data files with the selected rank were used to find loss margins, e.g., atmosphere loss calculated from the 99th percentile data file was taken as the margin required for 99% reliability.

Radiosonde profiles were ranked according to their columnar water vapor, defined as the total mass of water vapor in a cylinder with a 1 m^2 face, extending from ground level to the aircraft altitude. The columnar water vapor is

$$C = \sum_i \frac{\Delta h_i \rho_i}{1000} \quad \text{kg} \tag{1}$$

where Δh_i (m) is the thickness of shell i, and ρ_i is water vapor density (g/m^3) inside shell i.

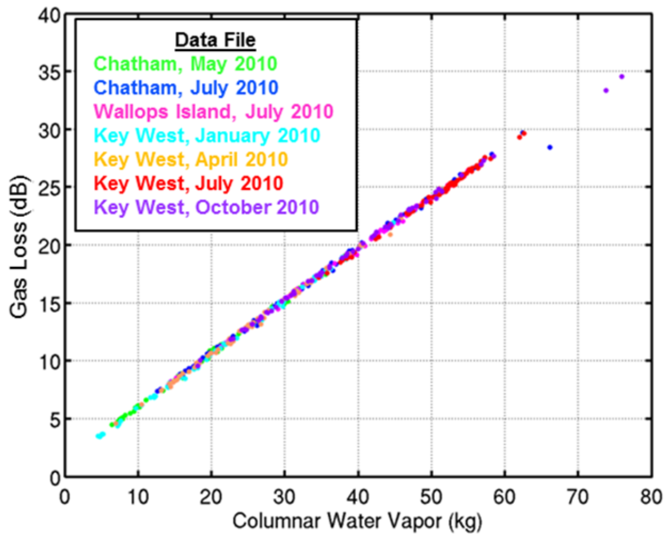
Figure 2 shows scatter plots of atmosphere loss versus columnar water vapor at two frequencies, for an air-to-ground path with aircraft altitude 35,000 feet (10.7 km), and ground range 120 nm (222 km). At this altitude, 120 nm ground range correspondes to a 2° elevation angle. Data was taken from five data sets, representing all three locations and every season.

Wator vapor absorption is the dominant loss mechanism near 22 GHz, and the 21 GHz data in Figure 2a forms a nearly perfect straight line. At 44 GHz oxygen absorption is also a factor. Oxygen absorption varies inversely with temperature, which does not affect columnar water vapor. However, oxygen loss is less variable than water vapor loss, and columnar water vapor was considered adequate for ranking weather profiles at 44 GHz.

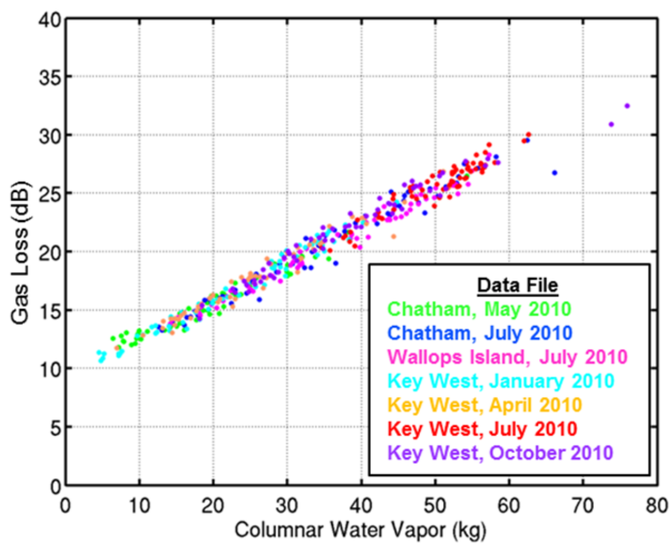
The Chatham Model

Figure 3 shows smoothed histograms of columnar water vapor in Chatham for each season. Note that in Chatham cool, dry months tend to have lower variation than warm, humid months because probability builds up near zero. At Key West the opposite effect is observed, hot wet months have less variability because the median approaches the maximum value obtained when humidity is 100%.

Figure 4 plots water vapor density versus altitude for some profiles from Chatham in July, ranked by their columnar water vapor. Figure 5 is a plot of atmospheric loss versus ground range at 21.7 GHz, for the radiosonde profiles of Figure 4. It also shows loss for the maximum and minimum columnar water vapor during the ten-year interval. Similar results were found at 44 GHz. The 44 GHz median loss at 120 nm (222 km) was slightly higher, but the 99th percentile loss at that range was about 3 dB lower. The spread was reduced at 44 GHz because oxygen absorption is less variable.



a. 20.7 GHz



b. 44.5 GHz

Figure 2. Scatter plots of gas loss versus columnar water vapor using data from different months and locations. Ground range 120 nmi (222 km), aircraft altitude 35,000 feet (10.7 km).

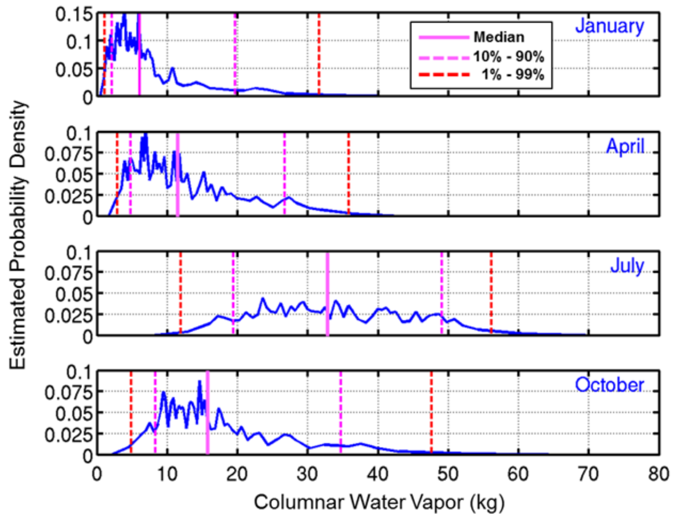


Figure 3. Columnar water vapor histograms for Chatham using radiosonde data from 2004 – 2013.

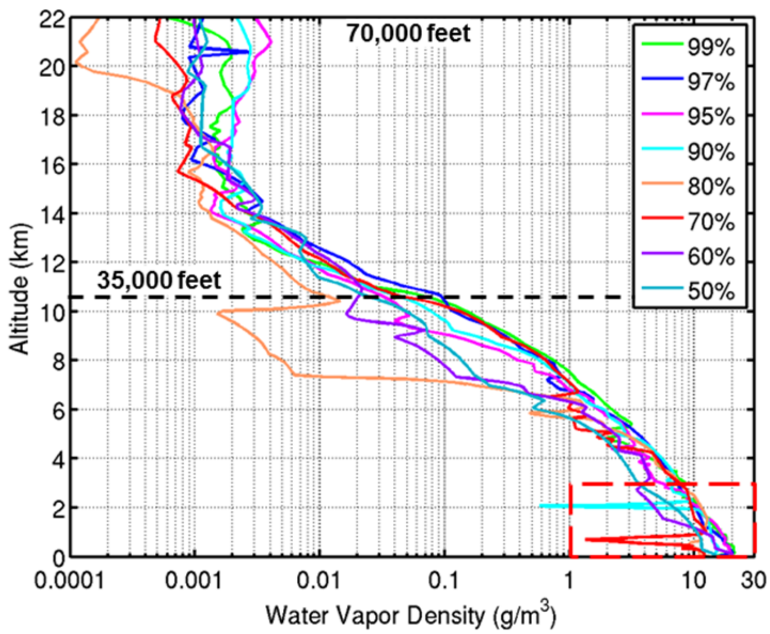


Figure 4 Water vapor density profiles from radiosonde recordings with indicated columnar water vapor rank over altitudes 0 – 35,000 feet (10.7 km), Chatham, July 2004-2013.

Figure 6 shows annual variation of columnar water vapor at Chatham, for representative percentiles. Figure 7 shows gas loss to an aircraft at 35,000 feet (10.7 km) altitude with 120 nm (222 km) ground range, using the radiosonde profiles corresponding to the percentiles in Figure 6. The 21 GHz median loss varies by by about 12 dB over a year, and 99th percentile loss varies by about 14 dB. Loss curves for the 44 GHz signal sometimes cross each other because files were ranked by columnar water vapor, which

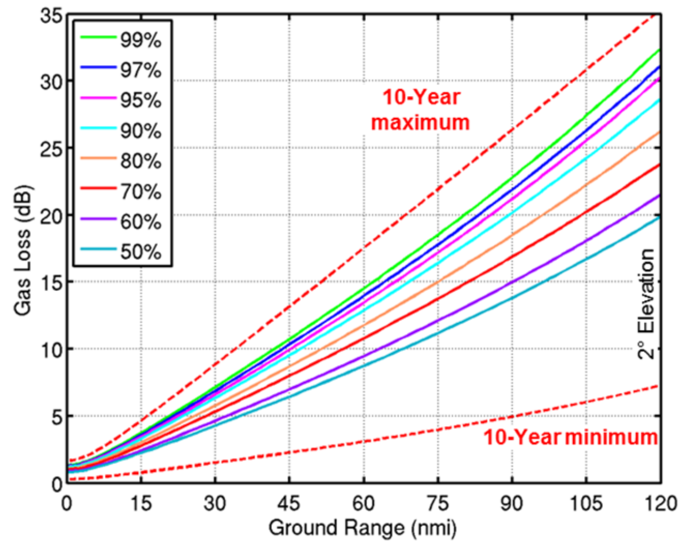


Figure 5. Atmospheric loss versus ground range for radiosonde profiles with indicated columnar water vapor, frequency 21.2 GHz, aircraft altitude 35,000 feet (10.7 km), Chatham, July, 2004 – 2013.

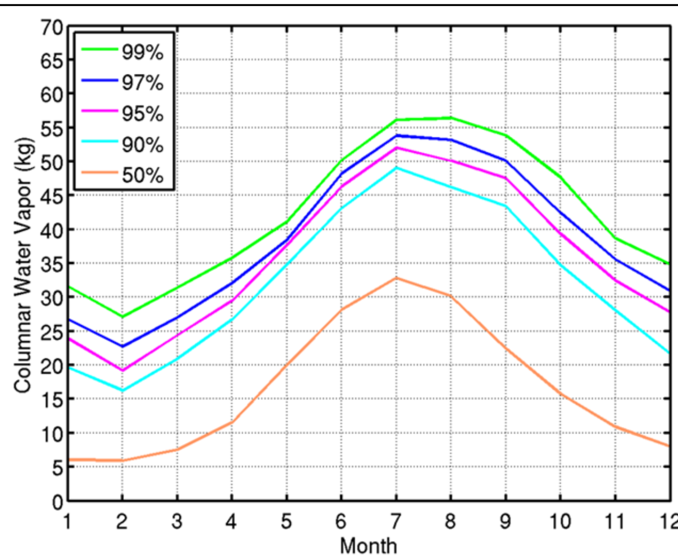


Figure 6. Columnar water vapor percentiles by month, Chatham MA, 2004-2013.

does not account for oxygen absorption. Oxygen absorption varies inversely with temperature, and may be high on cool dry days when columnar water vapor is low. The 44 GHz annual variation is 8-9 dB for the median, and about 12 dB for the 99th percentile.

Other Locations

Weather data was analyzed similarly for Wallops Island and Key West. Figure 8 shows annual variation in columnar water vapor at Wallops Island. Figure 9 shows gas loss at 120 nm (222 km) ground range to an aircraft at 35,000 feet (10.7 km) altitude, using the same radiosonde profiles as Figure 8.

Figure 10 shows columnar water vapor percentiles by month at Key West, and Figure 11 shows corresponding gas loss percentiles. The annual variation in median gas loss is 14 dB at 21 GHz, and 9 dB at 44 GHz. The annual variation to the 99th percentile line is less, 10 dB and 7 dB respectively.

Figure 12 compares propagation losses at all locations in July, the worst or near-worst month at each location, versus reliability. Reliability is the probability that observed loss will be no greater than the value indicated. For the data presented here, loss for a given reliability was estimated to equal the measured loss percentile. Curves are more variable at higher reliability because those estimates were based on events in the tails of the distributions, where there was less data.

Comparing both plots in Figure 12, loss increases as the location moves south to hotter, more humid climates but atmospheric loss variation decreases. The difference between locations is most pronounced at low reliability, becoming smaller as reliability increases. Wallops Island and Key West have almost identical downlink losses at 99% reliability, and Chatham loss is only 2-3 dB lower. This demonstrates again that there is a maximum vapor pressure which as approached in hot, wet climates, limiting the maximum gas absorption. An increase in humidity beyond the maximum results in clouds or fog, loss mechanisms that are not treated in this paper.

Conclusion

The availability of weather service data on the internet is a valuable resource for predicting performance of radio links above 10 GHz. Radiosonde profiles can be used to predict atmospheric propagation for a particular time and place. Historical collections of data allow us to predict power margins required to compensate for infrequently occuring conditions, by ranking past radiosonde profiles and identifying those causing high loss. As the quantity of historical data grows, increasingly improbable conditions can be modeled. This information can also be combined with weather prediction to plan for upcoming severe propagation weather events for operational systems.

As an example, available data from three weather stations along the east coast of the US were used to develop models that predict SHF/EHF air-to-ground link performance in a maritime environment. It was found that although there is significant variation in median performance from north to south, the margins required to achieve greater than 90% reliability vary by only few dB between Massachusetts and the southern tip of Florida.

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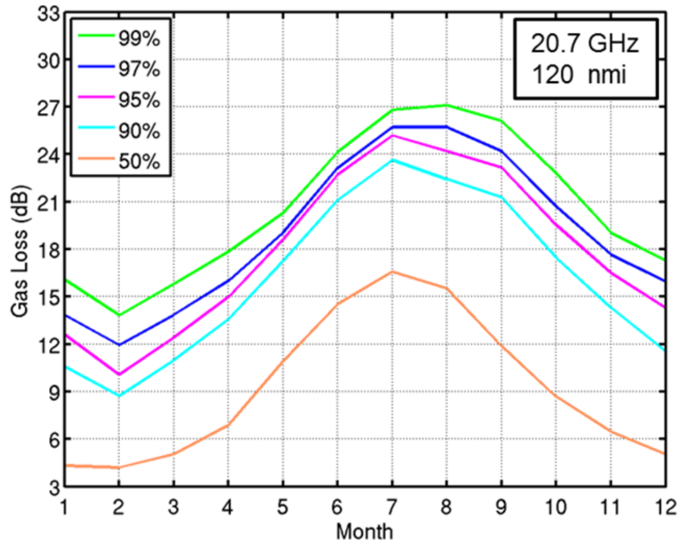
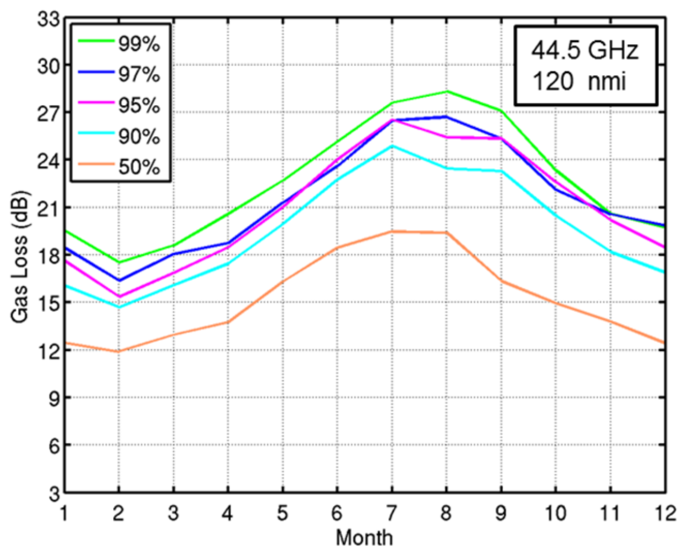


a. 20.7 GHz.



b. 44.5 GHz.

Figure 7. Atmospheric loss for indicated columnar water vapor percentiles by month, altitude 35,000 feet (10.7 km), ground range 120 nm (222 km), Chatham radiosonde data 2004-2013.

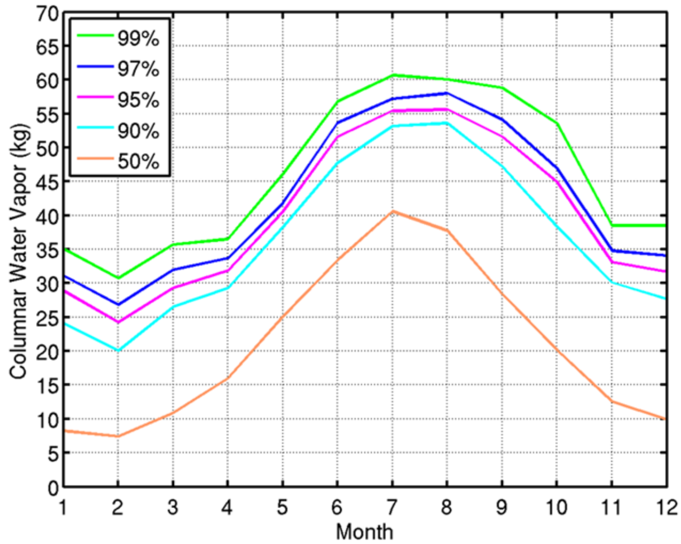
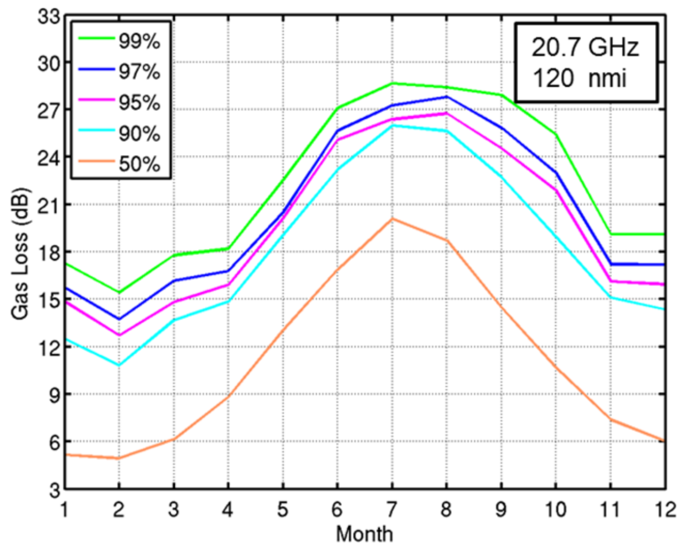
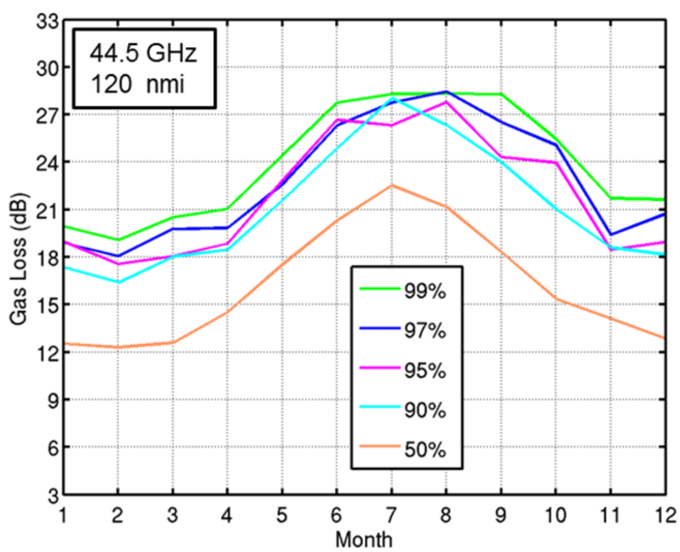


Figure 8. Columnar water vapor percentiles by month, Wallops Island, 2004-2013.



a) Downlink, 20.7 GHz.



b) Uplink 44.5 GHz.

Figure 9. Atmospheric loss for indicated columnar water vapor percentiles by month, altitude 35,000 feet (10.7 km), ground range 120 nm (222 km), Wallops Island radiosonde data 2004-2013.

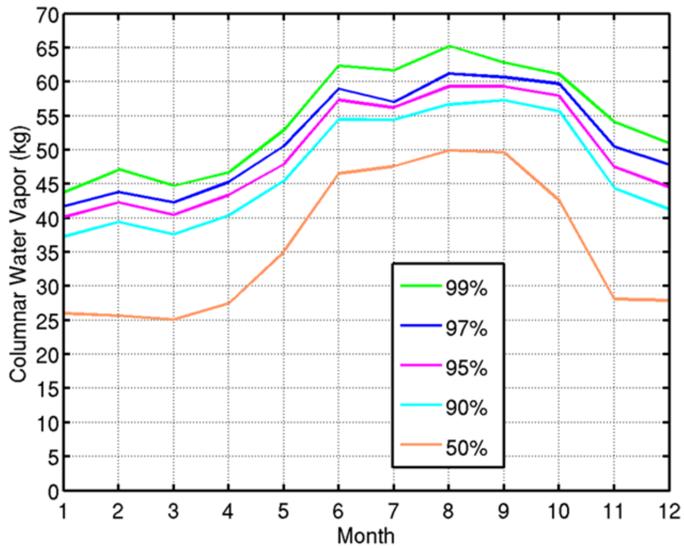
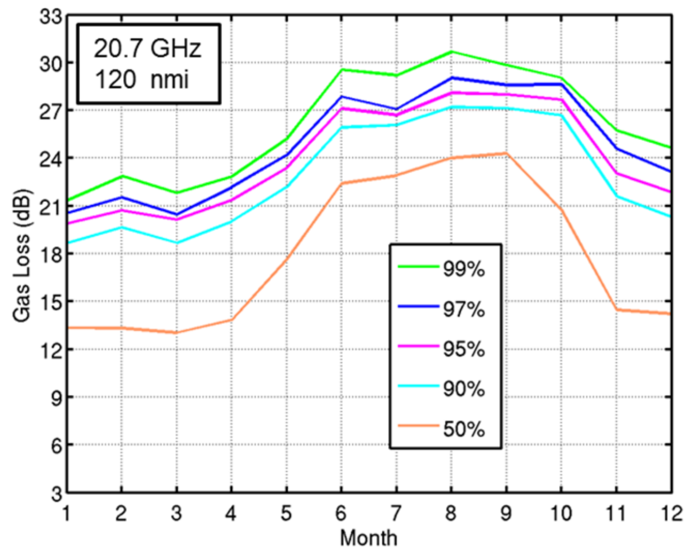
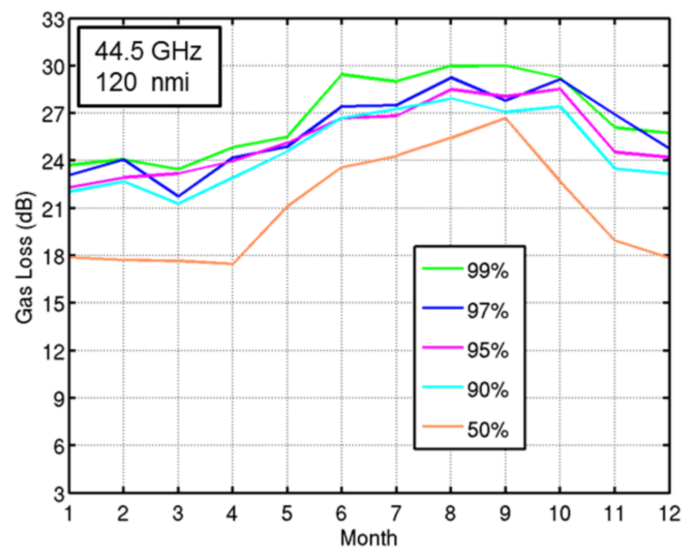


Figure 10. Columnar water vapor density percentiles by month, Key West, 2004-2013.

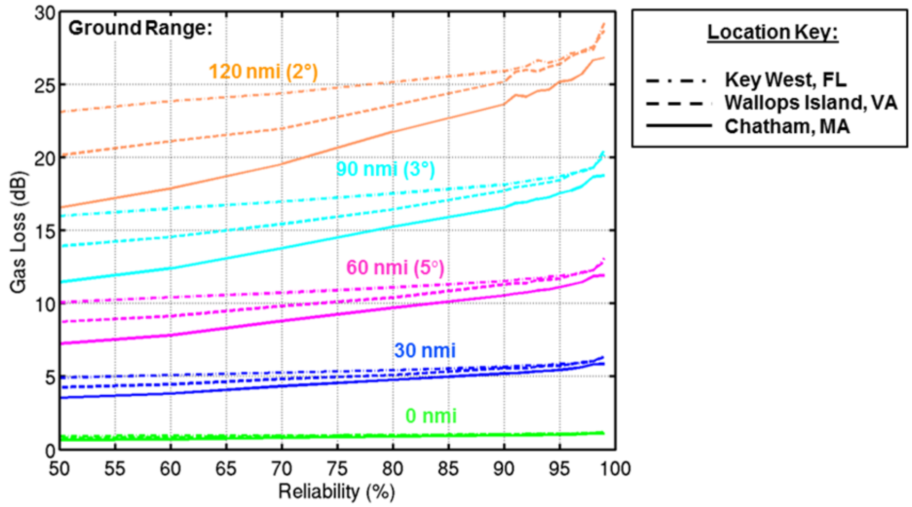


a) Downlink, 20.7 GHz.

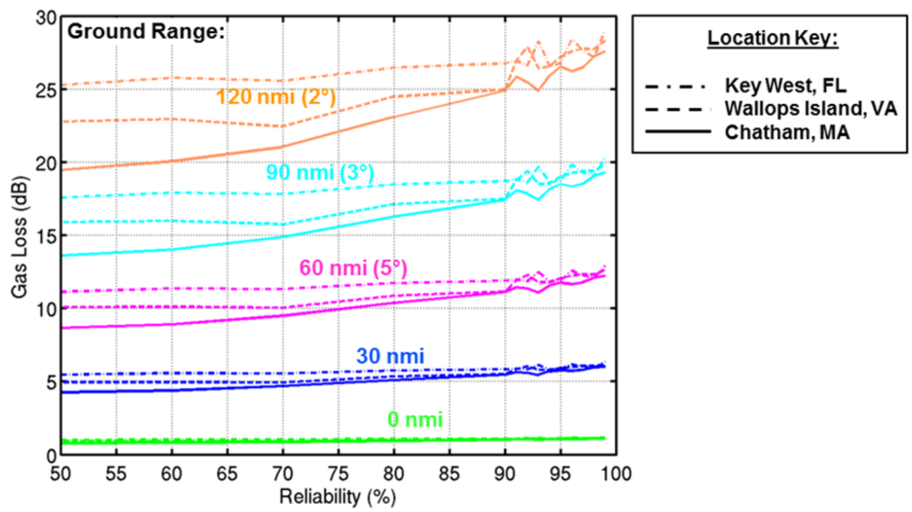


b) Uplink 44.5 GHz.

Figure 11. Atmospheric loss for indicated columnar water vapor percentiles by month, altitude 35,000 feet (10.7 km), ground range 120 nm (222 km), Key West radiosonde data 2004-2013.



b. 20.7 GHz



a. 44.5 GHz

Figure 12. Gas Loss margin versus reliability, parameterized by ground range. Aircraft altitude 10.7 km.