Radio Opacity Estimates for Giant Planet Atmospheres

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ABSTRACT

Estimating radio opacities in giant planet atmospheres is an interdisciplinary effort involving spectroscopy, planetary atmospheric science (both physics and chemistry), and geometry. Spectroscopy provides quantitative estimates of radio absorption by appropriate species, given their environmental conditions. Planetary science provides estimates, for each location of interest in an atmosphere, of the quantity of these absorbers and the environmental conditions. Then geometrical considerations allow integrating to yield the total opacity along a given signal propagation path. Uncertainties in both the spectroscopy and the atmospheric science combine to yield fairly sizeable uncertainties in opacity estimates, but nonetheless allow placing bounds on those opacity estimates that are useful for engineers designing telecommunications systems for entry probe missions. This paper discusses calculation of microwave opacity estimates and presents the preliminary results for Jupiter, Saturn, and Neptune.

1. Introduction and Background

There is strong scientific motivation for *in situ* sampling of our solar system's giant planets' atmospheres[1]. Among the science objectives currently considered best addressed by *in situ* sampling are vertical abundance profiles of primary volatiles, isotopic ratios of noble gases and other key constituents, atmospheric structure (temperature and pressure as a function of altitude), cloud density profiles and particle characteristics, radiant heat flow as a function of altitude, and abundance profiles of "diagnostic species" such as carbon monoxide that tell of conditions in inaccessible locations.

Analyses to determine the mission requirements stemming from the various science objectives reveals penetration depth requirements ranging from "shallow", 5-10 bar levels, to "very deep", deeper than 1000-bar levels. Unofficially, the breakpoint between relatively shallow and relatively deep involves water, the most abundant of the volatiles in giant planet atmospheres: above a given planet's water cloud is considered shallow, below its base is considered deep. But planet-to-planet environmental variation precludes any absolute definition of shallow and deep. "Below the typical water cloud base" at Jupiter includes pressure levels that are above the expected water cloud top at Neptune.

Returning high-priority science data from entry probes within giant planet atmospheres, especially deep within those atmospheres, depends critically on reliable knowledge of the RF propagation characteristics of the overlying atmosphere. Although refraction and scintillation can be important in some instances, absorption is usually the primary source of atmosphere-related relay signal attenuation. The science community usually refers to the absorptive aspect of a propagation medium as *opacity*, often expressed in units of *optical depths*, while radio engineers typically refer to *attenuation* in *decibels* (dB). This presentation uses the two interchangeably, but note that in both cases the reference signal characteristic is power, not electromagnetic field strength. An opacity of one optical depth produces the same signal attenuation as an opacity of $10\log_{10}e$ (~4.343) dB.

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At pressure levels up to at least a few hundred bars the microwave radio opacity behavior of giant planet atmospheres stems mainly from two chemical species in those atmospheres: ammonia (NH_3) and water (H_2O). Both species, especially ammonia, have presented challenges to researchers attempting to describe quantitatively the opacity due to these species under appropriate conditions, namely temperature, partial pressures of these species, and partial pressures of line-broadening gases such as hydrogen (H_2) and helium (He). Where many gases are fairly well described by formalisms derived from simplified quantum mechanical treatments, water and ammonia are "problem children" in spectroscopy, resisting such treatments. So far, formalisms for them are hybrids of theoretical predictions with significant empirical modifications[2]. Laboratory data from a number of researchers have allowed steady progress over the years, shrinking absolute error bars from factors of two or greater in the 1970's to tens of percent.

JPL has funded an internal task under which the most recent formalisms for ammonia and water opacity have been coded as subroutines and incorporated into software that, given an atmospheric model, calculates estimates of total vertical opacities vs. altitude in giant planet atmospheres. Similar software is found in the radiative transfer modeling codes used to interpret radio astronomical data, but the new software is intended primarily as an engineering tool. The atmospheric models must specify the partial pressures of the absorbing and broadening species, as well as temperature, as a function of altitude. Since there are uncertainties in atmospheric thermal models, and fairly large uncertainties in the absorber abundance profiles, no single model captures the uncertainty in vertical opacities. The new software allows quickly generating estimates for a range of physically plausible atmospheric models, thereby bounding the communications problem, to the extent that the atmospheric models capture the worst-case conditions.

Opacity estimates have been calculated using example atmospheric models for Jupiter and Saturn, and most recently for Neptune. Those results suggest that data relay from deep probes, especially at Neptune, will be difficult for single-hop relay links.

2. Structure of Planetary Tropospheres

Pressures, temperatures, and mass densities increase with depth for tropospheres in equilibrium. The local rate of the increase in pressure P is given by the *scale height*, H,

$$H = \frac{RT}{mg} \qquad (1)$$

where R is the universal gas constant, T is temperature, m is the average atmospheric molecular mass, and g is the local effective gravitational acceleration. At a given pressure level, temperatures at Saturn are somewhat lower than at Jupiter, but g at Saturn is about a third that of Jupiter, so Saturn's H is more than twice Jupiter's. Thus radio signals at a given pressure level at Saturn travel significantly farther to emerge. Figure 1 shows the T and P structure of those two tropospheres.

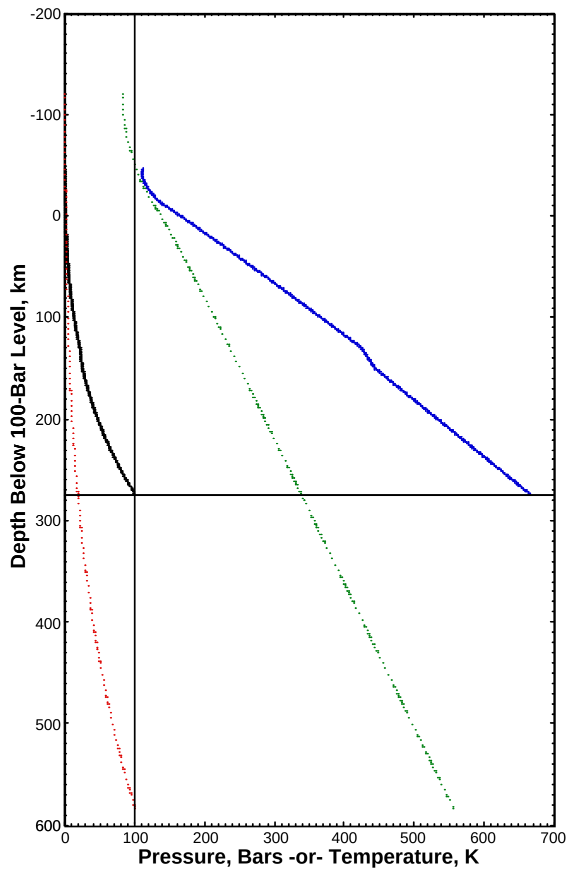

Figure 1. Tropospheric temperatures and pressures as a function of altitude at Jupiter and Saturn. The black and blue curves are pressure and temperature, resp., at Jupiter, and the red and green curves are for Saturn. The abrupt dogleg in the Jupiter curves is an artifact of appending deeper theoretical results to the Galileo Probe's observed data.

As temperature increases, atmospheric constituents that condense out of the cold upper levels are no longer limited by vapor pressure saturation, and can reach their deep abundances. Some such constituents, notably ammonia and water, are strong radio absorbers. The planet-to-planet variation of H and T profiles prevents generalizing opacity calculations from one planet to another.

3. Radio Signal Absorption by Gases

Most gases absorb radio-frequency electromagnetic radiation due to rotational or vibrational absorption lines in the infrared. This makes them weak absorbers at radio frequencies, in the far low tails of those absorption lines. But absorption lines can be greatly broadened by frequent molecular collisions, and higher pressures greatly increase this effect. Figure 2 illustrates the "pressure broadening" of a line, broadened only by Doppler broadening in the left panel, then mildly pressure-broadened (note the drop in amplitude at the peak, increase in the wings) in the center panel, then more severely pressure-broadened. Note that in the right panel the frequency scale is compressed, and asymmetry of the line, a natural effect of severe pressure broadening, is now evident.

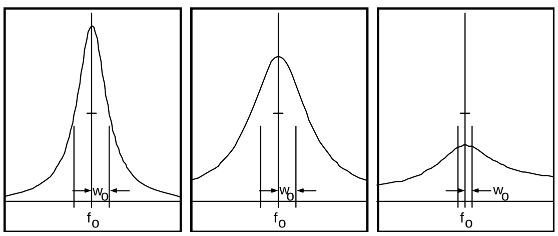

Figure 2. Progressive pressure broadening of an isolated absorption line.

Ammonia and water are notable because they have fairly strong absorption lines at radio frequencies (but those lines are still weak compared to the powerful IR lines), and they are relatively abundant in giant planet atmospheres, so they dominate radio opacity in those atmospheres. The three panels of Figure 3 illustrate the change in ammonia's absorption spectrum with increasing pressure broadening, from an essentially un-broadened line spectrum to one dominated by the low tails of the IR lines.

4. Calculated Radio Opacity Estimates

The new software used to calculate these opacity profiles consists of two primary elements. One is a set of absorptivity calculation subroutines that calculate the radio absorption coefficients for each of the absorbing gases under given conditions of temperature, pressure, *etc*. The other is an atmosphere integrator that calculates the vertical opacity in each 1-km interval from the top of the atmosphere, *i.e.* the level at which the overhead opacity is essentially zero, down to the level of interest, and sums those opacities over the vertical interval. This software currently does not calculate opacity due to clouds or absorbing species other than water, ammonia, and hydrogen. Atmosphere models used in the calculations are not fully accurate and are intended to show general tendencies only, so they are not yet appropriate for use in space mission detailed design.

Jupiter

Figures 4-7 are charts of vertical radio opacity at two different frequencies: 401 MHz, in the UHF part of the radio spectrum, and 1.3 GHz, near the Galileo Probe radio relay link frequency in the "L-band" part of the spectrum. Note the large differences in scales of the opacity axes. Figures 4 and 5 are based on atmosphere models whose deep abundances of both water and ammonia are the same as solar abundances of oxygen and nitrogen, respectively. Figures 6 and 7 models have deep water and ammonia abundances 5 times the solar values. Jupiter's powerful radiation belts, unique among the giant planets, influence the

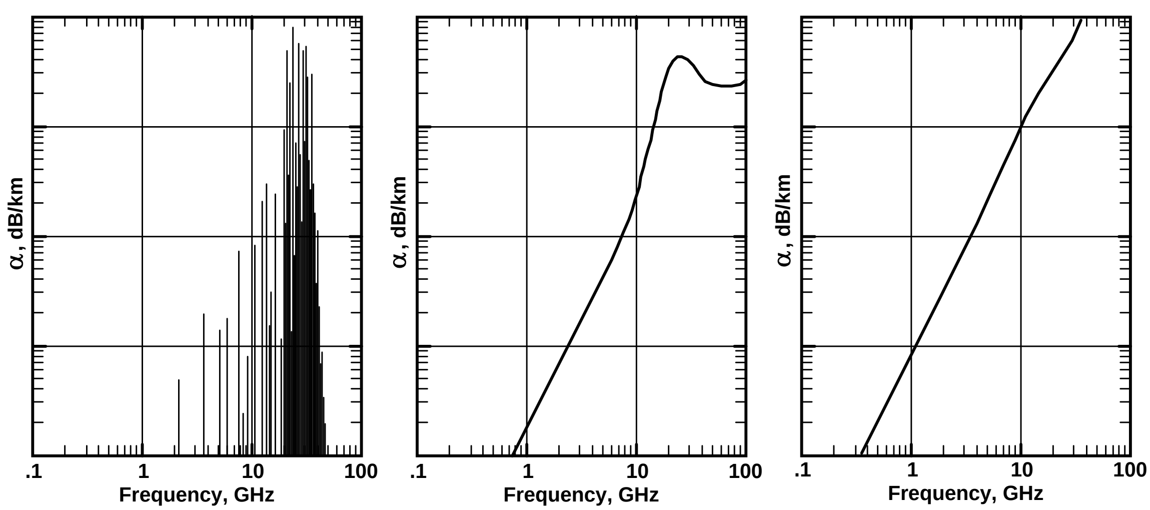

Figure 3. Progressive pressure-broadening effects on ammonia's microwave absorption spectrum.

choice of relay link frequency by adding synchrotron radiation noise to the situation. That noise increases rapidly as frequency decreases from ~2 GHz to its peak at ~300 MHz, so the best SNR occurs in L-band, not at lower frequencies where atmospheric opacity is smaller.

Saturn

Figures 8-11 mirror the Jupiter charts in radio frequencies and absorber abundances. Again, note the large differences in scales of the opacity axes, in this case nearly two orders of magnitude. Figure 12 is a vertical opacity profile from an atmospheric model with the ammonia deep abundance the same as solar nitrogen but the water abundance 5 times that of solar oxygen. This hybrid model can be viewed as a simulation of the "solution cloud" situation, where ammonia dissolves in water cloud droplets, causing its abundance above the water cloud to be less (possibly much less) than its deep abundance. Compare this profile with the part of Figure 11 above the 20-bar level. Note that at 10 bars this model's opacity is about a fifth that of Figure 11, consistent with an ammonia abundance between the ammonia and water clouds that is a fifth of that model. But below the top of the water cloud, water opacity causes the total opacity to increase more quickly.

Neptune

Recently models of Neptune's atmosphere have been adapted for use by the new software, and preliminary results calculated. Note in Figure 13 how Neptune's colder atmosphere pushes the radio-absorbing species deeper into the atmosphere, but below their saturation (cloud-forming) levels the opacity increases quickly. Compare the opacity at the 100-bar level to those at Jupiter and Saturn at similar frequencies.

5. Summary and Conclusions

At radio frequencies useful for entry probe communications, calculated vertical opacities at the various giant planets' 100-bar levels range from ~10 dB to over 100 dB (at Neptune). When the opacity exceeds ~15-20 dB it is difficult to envision probes as currently implemented being able to return useful data to an overhead spacecraft, not to mention directly to Earth. *In situ* measurements of the deep abundances of some important volatiles would require radically new entry probe architectures, such as "staged probes" that leave sub-probes at higher altitudes, for communications relay and perhaps science measurements focused on the upper troposphere. That particular architecture is attractive because it allows the shallow element, with its higher relay link data rate, to fold in the lower-rate deep probe data in parallel with its own shallow data.

If volatile abundances are less than anticipated -- which would be a surprise, but cannot be ruled out as yet -- the prospect of deep probes penetrating the water clouds at Jupiter and Saturn is better, but still difficult. Such missions would be hampered by low data rates.

Further work can include the full range of plausible atmospheres for Jupiter and Saturn, and extension to Uranus and Neptune. Also, opacity estimation routines for less abundant absorbers such as hydrogen sulfide (H_2S) and phosphine (PH_3, the phosphorus-centered equivalent of ammonia) can be added.

6. Acknowledgments

This work was funded by and performed at the Jet Propulsion Laboratory, California Institute of Technology.

7. References

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2. "Laboratory Measurements of Microwave Absorptivity and Refractivity Spectra of Gas Mixtures Applicable to Giant Planet Atmospheres," Stanford University Ph.D Dissertation, 1990.

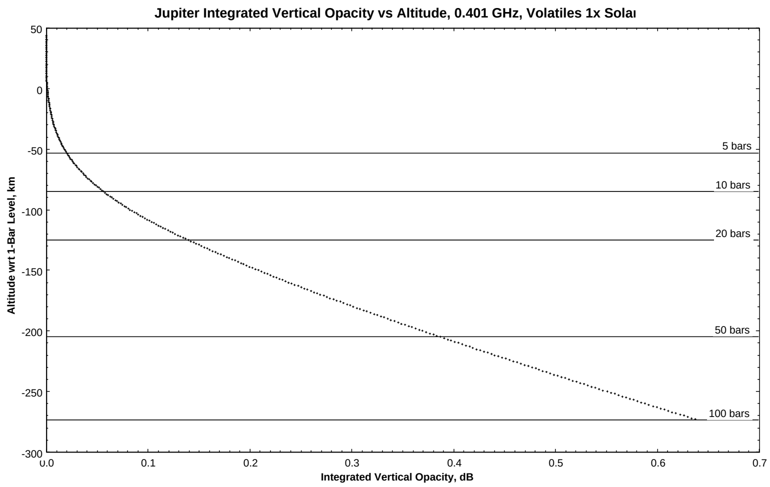

Figure 4. Jupiter vertical opacity profile at 401 MHz, solar absorber abundances.

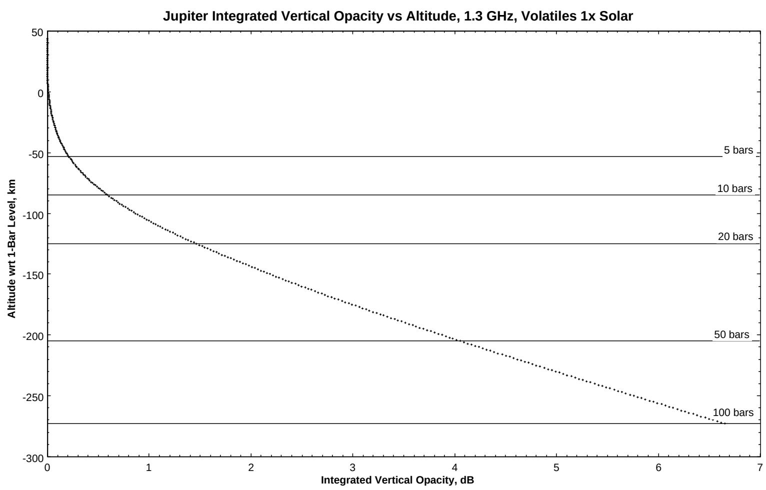

Figure 5. Jupiter vertical opacity profile at 1.3 GHz, solar absorber abundances.

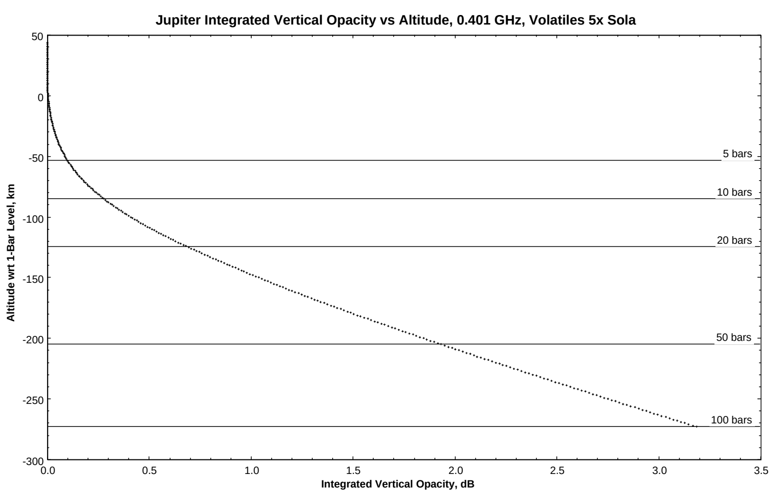

Figure 6. Jupiter vertical opacity profile at 401 MHz, five times solar absorber abundances.

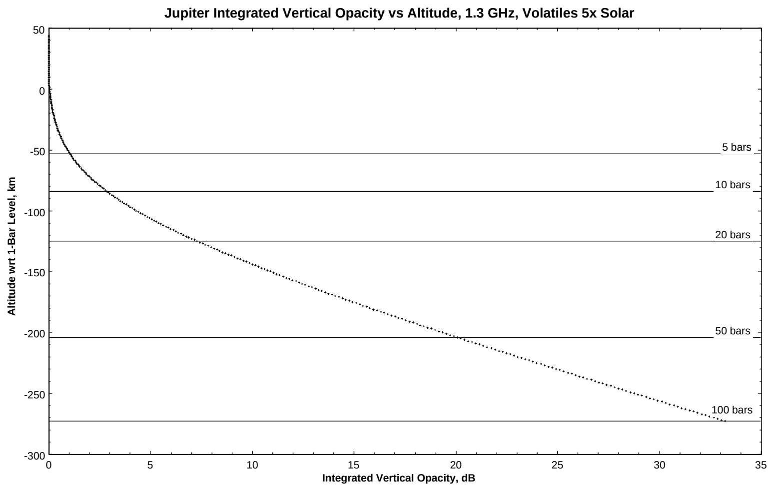

Figure 7. Jupiter vertical opacity profile at 1.3 GHz, five times solar absorber abundances.

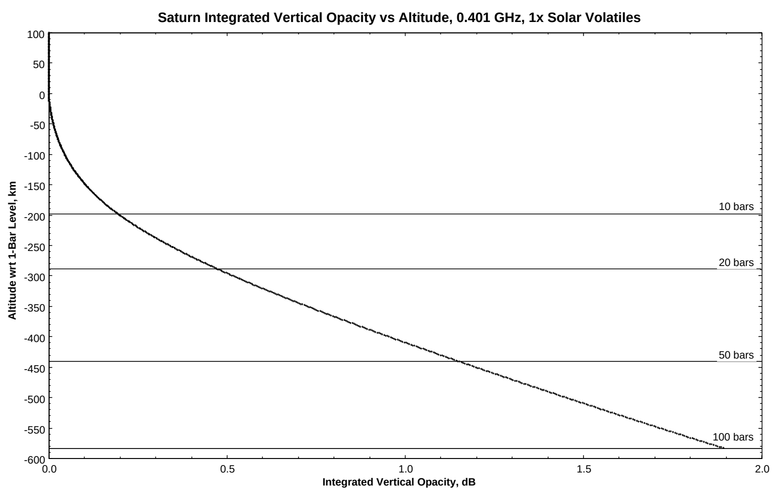

Figure 8. Saturn vertical opacity profile at 401 MHz, solar absorber abundances.

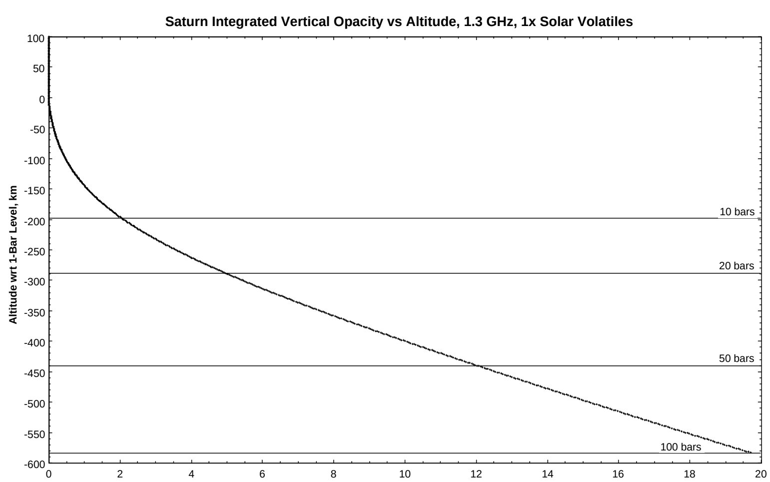

Figure 9. Saturn vertical opacity profile at 1.3 GHz, solar absorber abundances.

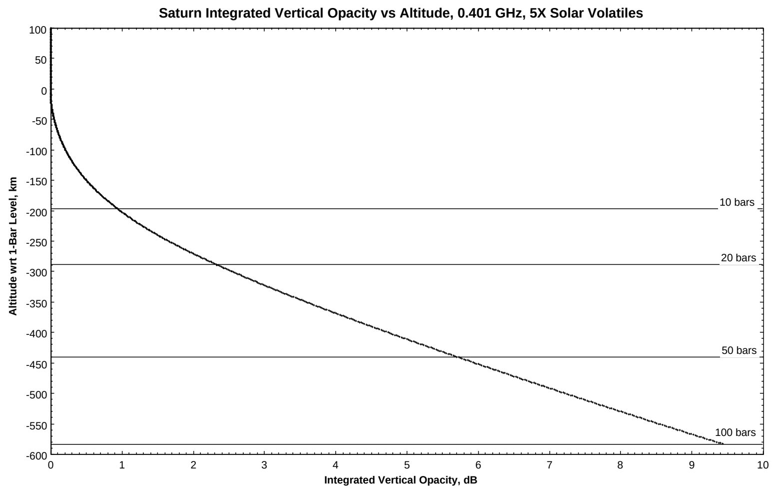

Figure 10. Saturn vertical opacity profile at 401 MHz, five times solar absorber abundances.

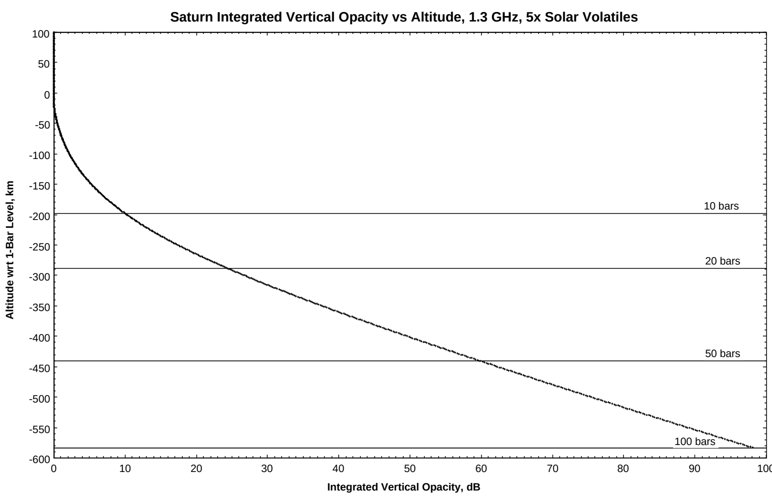

Figure 11. Saturn vertical opacity profile at 1.3 GHz, five times solar absorber abundances.

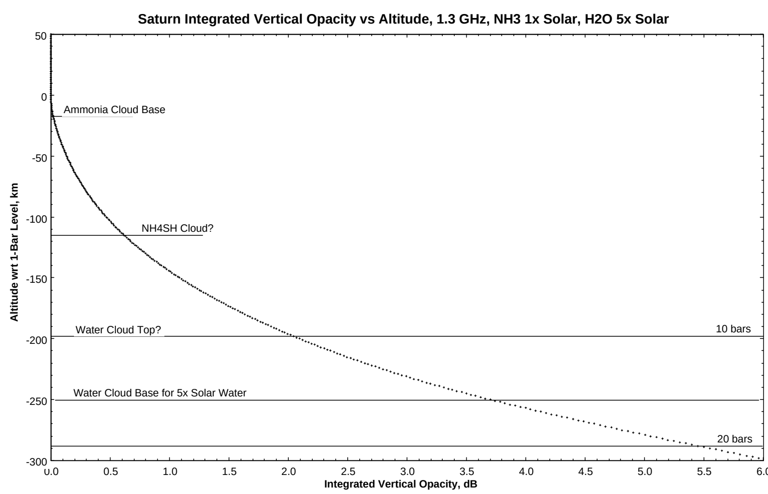

Figure 12. Saturn vertical opacity profile at 1.3 GHz, solar-abundance ammonia, five times solar water.

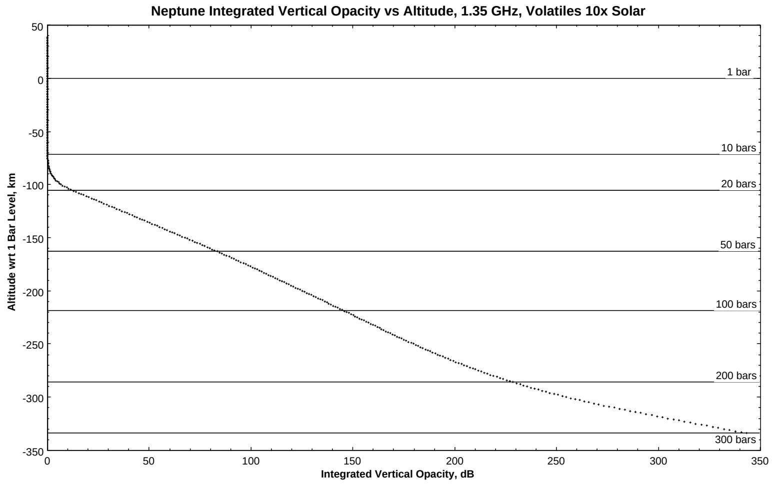

Figure 13. Neptune vertical opacity profile at 1.35 GHz, ten times solar absorber abundances.