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Hole-Boring through Clouds for Laser Power Beaming

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ABSTRACT

Power beaming to satellites with a ground-based laser can be limited by clouds. Hole-boring through the clouds with a laser has been proposed as a way to overcome this obstacle. This paper reviews the past work on laser hole-boring and concludes that hole-boring for direct beaming to satellites is likely to require 10-100 MW. However, it may be possible to use an airborne relay mirror at 10-25 km altitude for some applications in order to extend the range of the laser (e.g., for beaming to satellites near the horizon). In these cases, use of the relay mirror also would allow a narrow beam between the laser and the relay, as well as the possibility of reducing the crosswind if the plane matched speed with the cloud temporarily. Under these conditions, the power requirement to bore a hole thorugh most cirrus and cirrostratus clouds might be only 500-kW if the hole is less than 1 m in diameter and if the crosswind speed is less than 10 m/s. Overcoming cirrus and cirrostraus clouds would reduce the downtime due to weather by a factor of 2. However, 500 kW is a large laser, and it may be more effective instead to establish a second power beaming site in a separate weather zone. An assessment of optimum wavelengths for hole boring also was made, and the best options were found to be 3.0-3.4 μm and above 10 μm.

Keywords: Laser power beaming, cloud hole-boring

1. INTRODUCTION

Clouds have always been a problem for laser power-beaming. One possibile solution is to use laser power to bore a hole in the clouds along the line of sight to the satellite. Beaming directly to a low-earth-orbit (LEO) satellite will require a beam diameter of about 1 m, and beaming to geostationary-earth-orbit (GEO) satellites will require about 5-10 m. The hole-boring laser would need to provide enough power to clear the channel and keep it clear as wind swept across it (or as the laser tracked the satellite.)

It has been proposed recently to use an airborne relay mirrors to enhance some power-beaming missions,[1,2] and this may allow hole-boring with less power. In the relay concept, the laser beam is directed to a mirror on an airplane stationed high above the laser site. From there the beam is directed to the satellite for use. The chief advantage of this system is the ability to access satellites which are very low on the horizon without suffering losses from a long slant range through the atmosphere. One possible application is to beam power (via the relay mirror) to orbital transfer rockets in LEO where beaming time is severely limited. Another is to beam power via the relay mirror to a constellation of LEO communication satellites while they are in the earth's shadow. When an airborne relay mirror is used, the optical leg from the ground to the mirror is less than 30 km, so the beam diameter can be kept small. This reduces the power required for hole-boring through clouds and may thus enhance the laser availability for these missions.

2. CLOUD TYPES AND CHARACTERISTICS

The major types of clouds are shown in Figure 1. They range in thickness from 100 m to 10 km, and in altitude from 100 m to 10 km. Cirrus clouds are the thinnest and are composed of ice crystals. Cumulonimbus clouds are the densest and thickest. There is considerable variation in clouds and, also, some uncertainty in the frequency of occurrence of the key cloud parameters, but Table 1 gives typical base altitude, thickness, and liquid (or ice) density.[3-6] Ice clouds are the simplest to penetrate because the overall ice density is low and the surrounding humidity is low. A good measure of difficulty in

penetration is the equivalent thickness of water, which is the layer that would be produced if all the liquid drops (or ice crystals) were collapsed to a single level. This value is shown in the last column of Table 1.

Additional water is present as vapor, which is transparent and nonscattering to visible light. Indeed, the mass density of the water vapor in a cloud is often 1-10 g/m^3, which is about ten times the cloud density in the liquid state. This implies that the total vapor in a channel will not increase much when the channel is formed. Figure 2 shows the saturated vapor density of air versus temperature and altitude versus temperature. (The dotted line shows how to go from a given altitude to the corresponding saturated vapor density.) The air temperature drops linearly with altitude to about -50 °C at 10 km. So the vapor density in a cloud is usually less than near the ground, even in the deserts. This means that the vapor added to the air during channel formation in most clouds will not significantly alter the laser beam propagation compared to the water vapor in the rest of the beam's path.

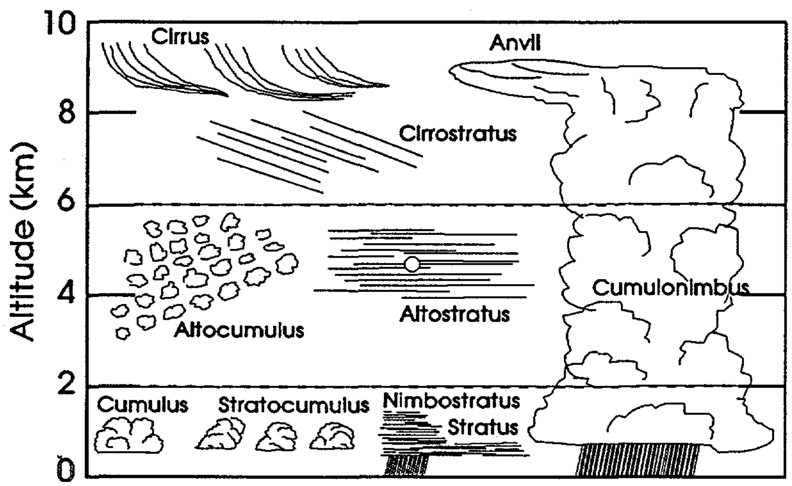

Figure 1. Various types of clouds

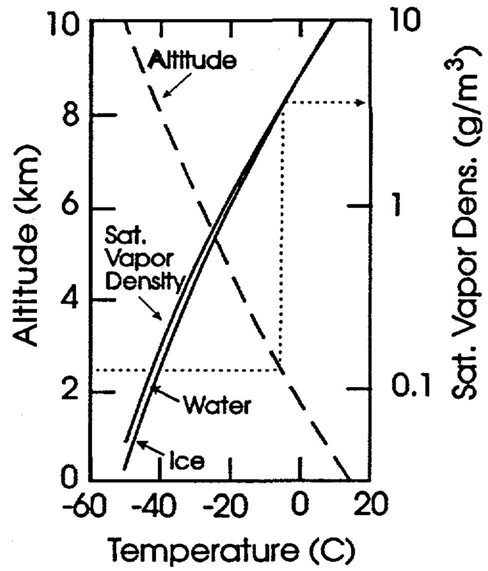

Figure 2. Altitude and saturated vapor density versus temperature.[3]

Table 1. Mean Properties of Cloud Types.[3-6]

Cloud Type	Composition	Base (km)	Thickness (km)	Ave Drop Radius (μm)	Liquid Density (g/m^3)	Equivalent Thickness of Water (mm)
Cirrus (Ci)	ice	6-10	0.2-3	40	0.005	0.00-0.02
Cirrostratus (Cs)	ice	5-7	2-3	40	0.005	0.01-0.02
Altostratus (As)	ice	3-6	1-3	40	0.020	0.02-0.06
Altocumulus (Ac)	water	2-6	0.3-1.5	5	0.10-0.35	0.03-0.50
Stratus (St)	water	0.1-1	0.5-1	5	0.10-0.45	0.05-0.45
Stratocumulus (Sc)	water	0.5-2	0.5-1.5	5	0.15-0.35	0.08-0.50
Nimbostratus (Ns)	water	0.1-1	1-5	5	0.10	0.10-0.50
Cumulus (Cu)	water	0.5-2	1-3	6	0.10-0.20	0.10-0.60
Cumulonimbus (Cb)	water	0.4-1.5	2-10	10	0.10-2.00	0.20-20.00

Table 2. Annual probability of different cloud types being in a line of sight upward.

Cloud Type	Nevada Test Site	White Sands
None	58%	57%
Cirrus	14%	15%
Cirrostratus	10%	7%
Altocumulus	6%	9%
Stratocumulus	4%	5%
All others	8%	7%

The frequency of occurrence for various cloud types depends heavily upon location. However, for the primary power-beaming candidate sites in the American southwest, there is a fair amount of similarity. Table 2 summarizes the annual probability of different cloud types being along a particular line of sight upward. The two desert sites considered are Yucca Flat at the Nevada Test Site (NTS) and El Paso, Texas, which is near the White Sands Missile Range (WSMR) in New Mexico. Cloud conditions at China Lake, California, an excellent power-beaming candidate site,[1] should be similar to, but slightly clearer than, the Nevada Test Site.

The annual percentages of possible bright sunshine for NTS and WSMR are given as 72% and 68%, respectively.[1] This apparent discrepancy with Table 2 is due to the fact that cirrus and cirrostratus clouds are often partially transparent. This allows some bright sunshine to penetrate, but would cause degradation in power-beaming performance. About 80% of all the clouds at these sites are composed of the four types listed in Table 2. The percentages during equinoxes are about the same as the annual percentages. (At the Nevada Test Site, spring is worse than average, and fall is better than average.)

3. HOLE-BORING MODELS AND EXPERIMENTS

Laser hole-boring through clouds and fog has been studied for several decades. Much of this effort has centered around using CO_2 lasers because the 10.6-µm wavelength is absorbed well in liquid water but hardly at all in water vapor. Sutton has published a model for hole-boring through an optically thick fog or cloud.[7] He considered the effects of absorption in the droplets, and scattering of light to outside the channel. After considerable theoretical analysis involving integration of scattering and absorption coefficients over spherical droplets, he derived a fairly simple formula that predicts the rate at which a channel will penetrate into a thick fog. The model states that the energy needed to form the channel is equal to the total energy needed to vaporize all the liquid in the channel volume, times a factor allowing for the ratio of scattering to absorption. The energy fluence required is:

$$F = \left(h_v + C_p \Delta T\right) h_v \rho_l L \left(1 + \alpha_s / 2\alpha_a\right), \tag{1}$$

where h_v is the heat of vaporization of water, C_p is specific heat of water, ΔT is the temperature increase from ambient to the vaporization point (nominally 50°C for these conditions), ρ_l is the density of liquid water in the fog (typically 1 g/m^3), L is the length of the channel, and α_s and α_a are the extinction coefficients for scattering and absorption, respectively. (The $C_p\Delta T$ term has been added to Sutton's model to allow for droplet heating prior to evaporation.) Conduction to the surrounding medium is ignored. For 10.6-µm light and most fog and cloud droplet size distributions, $\alpha_s/\alpha_a = 1$.

Volkovitsky, Sedunov, and Semenov wrote a very comprehensive summary of Russian research encompassing the past thirty years.[5] It is a 337-page book with 254 technical references, most of them Russian, and is the most definitive publication on the subject. They have various detailed models for evaporation of water droplets and ice crystals that include the effects of absorption, scattering, thermal conduction, recondensation from supersaturated vapors, and wind across the channel. They report on a substantial experimental data base that validates the models, primarily in the regime where there is no recondensation of the evaporated droplets. In the simplest forms, their models are similar to Sutton's model, but in their complete forms they are capable of handling a greater range of conditions.

Waggoner and Radke[8] note that recondensation of evaporated droplets is very likely to be the rule, rather than the exception. The reason for this is that the air within a cloud is probably saturated, or even a bit supersaturated. When a droplet evaporates, its vapor mixes with the surrounding air making it very supersaturated, and the vapor then will recondense spontaneously, either on the local nuclei or back on the original droplet. Much of the channel formation work appears to have been performed with subsaturated conditions, leading to good agreement with models that have neglected recondensation. But when saturated air is used, recondensation is observed. Russian researchers have photographed this effect with high-speed cameras.[5,9]

It does not take much temperature increase in the local air to accommodate the extra vapor coming from the vaporizing droplets. Most clouds have liquid densities of about 0.2 g/m^3, and Figure 2 shows that a small increase in the air temperature by a few degrees or less is all that is needed to accommodate this additional mass. Waggoner and Radke[8] note that this can be accomplished by repeated vaporization and recondensation steps, or by partial absorption by the water vapor itself. Indeed, they develop a formula for determining how many cycles are required, and for most clouds it takes only two or three cycles. Chitanvis[10] has developed a model that explicitly includes recondensation.

Waggoner and Radke[8] also have proposed that for ice clouds, recondensation will not be a problem because the local vapor concentration will remain below the dew point even after ice melting and vaporization. This is an important proposal, and they note that many experiments did not use prototypic vapor densities, ice mass densities, or temperatures. Because of this, the result of previous experiments on recondensation could be misleading. They suggest that some of the melted ice will evaporate spontaneously, utilizing the heat stored in the surrounding air. They demonstrated this phenomenon experimentally[11] and showed that for ice clouds, a 2-J/cm^2 CO_2 laser pulse results in a clear channel that persists for over two minutes. A pulse of only 0.2 J/cm^2 reduced absorption by about a factor of ten, and this also persisted for many seconds. Models have been developed to predict and explain these experimental results.[11]

Experimenters also have determined that a high-flux laser pulse can shatter the droplets into a fine mist.[5,12-15] This mist then can evaporate more rapidly with the increased total surface area. Or, if the droplet diameters in the mist are all less than about 0.3 μm, visible or near-IR light will not be scattered much, and subsequent evaporation may not be necessary. The shattering process relies on heating the interior to above the spontaneous nucleation temperature. Kafalas and Ferdin[12] first observed this effect in 1973 for laser fluence levels above 3 J/cm^2 with 40-50-μm droplets. Volkovitsky, et al., also report this effect in their book.[5] Pinnick, et al.,[13] have demonstrated droplet breakup at about 3 J/cm^2 for droplets ranging from 10 to 60 μm using a 25-μs CO_2 laser.

Quigley,et al,[14] have demonstrated droplet breakup at 1.2 J/cm^2 with a flux of about 300 kW/cm^2. They suggest that the threshold fluence for breakup is 50 kW/cm^2. They also demonstrated that a total fluence of 10 J/cm^2 cleared a channel in which light absorption was reduced by a factor of 10. The 5-cm diameter channel remained clear for about 0.5 seconds, and began closing from turbulent mixing, rather than recondensation. (The initial saturation of the surrounding air was not reported.) However, when the fluence was 2 J/cm^2, the laser pulse actually increased absorption because the pulse shattered the droplets, but there was not enough subsequent laser energy to vaporize the shattered droplets. For thick clouds, one could crudely assume that the energy needed to shatter droplets through the cloud (optimistically assuming transparency after shattering) is 1.2 J/cm^2 times the number of optical thicknesses in the cloud. Several models have been developed to explain the experimental results.[5,10,16]

4. Hole-Boring Predictions

Table 3 shows the predictions of various models for a number of representative clouds. The cloud liquid density and thickness are combined into an equivalent thickness of water. The fifth column shows the predictions of Sutton's model, and the next shows Volkovitsky's model. Both of these assume vaporization without subsequent condensation. To allow for the possible need to overcome recondensation with multiple (nonshattering) pulses, the energy requirements predicted by Volkovitsky are increased by the number of pulses specified by Waggoner and Radke's model in the next column. The final column is for the crude shattering model described in the previous paragraph.

There is considerable difference between the models because of the different phenomena assumed. The shattering model is probably too optimistic, and the multiple pulses of Waggoner may not be needed if a crosswind requires refreshing the channel faster than recondensation occurs. (Chitanvis calculates that recondensation takes about a second.[10]) The clearing requirements for the cirrus ice clouds may be lower than the models predict if the melted crystals evaporate on their own. On the other hand, cirrus clouds tend to be thin, so much of the laser energy passes through the cloud anyway. So the two effects may offset each other to first order. In general, there is an uncertainty of at least a factor of 2 in required energy for a given cloud. However, the variation in possible cloud configurations is much greater than a factor of 2, so this uncertainty is not too important for this scoping paper. So we will adopt Sutton's model for simplicity and use it for predicting laser *requirements.*

Table 3. Fluences needed to clear a hole in various cloud types, according to various models, with different assumptions.

Cloud Type	Liquid Thickness (mm)	Optical Thick-nesses	Temp-erature (°C)	Sutton (J/cm^2)	Volkovitsky (J/cm^2)	Waggoner; Volkovitsky (J/cm^2)	Shattering (J/cm^2)
Cs	0.01	1	-44	3.6	3.0	2.4	1.5
As	0.03	3	-26	11	9	10	4.5
Ac	0.10	10	-14	36	30	43	15
Ac	0.50	50	-14	180	150	216	75
Sc	0.10	10	4	36	30	87	15
Sc	0.50	50	4	180	150	433	75

To keep a channel clear requires a repetitively pulsed laser with a high-average power, or a true CW laser. It may not be possible to remove the droplets entirely with a CW laser because conduction losses to the atmosphere will eventually equal absorption gains, and the evaporation process will stop. However, if the droplets are smaller than 0.3 μm when this occurs, the channel will be essentially transparent to visible and near-IR light.

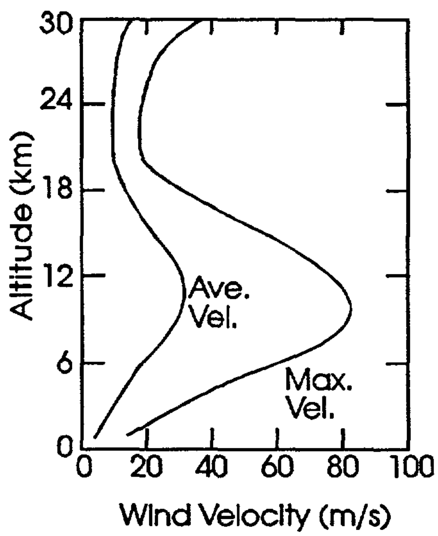

Figure 3. Wind speed versus altitude at China Lake, CA.

The total laser power required depends on the hole diameter (d_h) and the wind speed. The airborne relays are envisioned to be at 20-25 km altitude where the local wind speed is minimum. If the relay is limited to zenith angles of 30°, the range will be 30 km or less. If λ is the wavelength for the hole-boring laser and β is the divergence relative to the diffraction limit, then the minimum Gaussian beam diameter for a uniform beam of length R is:

$$d_b = \sqrt{2.44\lambda R\beta}\ . \qquad (2)$$

For λ = 10.6 μm, R = 30 km, and β = 1.3, we have d_b = 1.0 m.

The prevailing wind will continuously bring new cloud material into the hole. Figure 3 shows the average wind speed and maximum recorded speed at China Lake, California.[1] Winds as high as 80 m/s (160 knots) are possible in the jet stream at a 10-km altitude, but usually clouds move at less than 30 m/s (60 knots).[1,2,15] The winds at a 20-km altitude are 20 m/s maximum, so the relay platform needs to handle up to 20 m/s to stay over the power-beaming site. For a 1-m diameter hole, a 10-m/s wind corresponds to a refresh time of 0.1 seconds. This refresh time may be short enough to overcome recondensation within the channel, which generally occurs in about a second, [9,13] and thus eliminate the need to heat the air sufficiently to absorb the additional water.

If we assume that the channel must penetrate the cloud in the same time that it takes the relative wind to cross the channel, then a simple formula for the thickness of cloud that can be penetrated before the relative wind refills the channel is:

$$t_c = \frac{4P_L}{\pi d_b v_w \left(h_v + C_p \Delta T\right)\rho_l (1 + \alpha_s / 2\alpha_a)}, \qquad (3)$$

where t_c is the thickness of the cloud, P_L is the power of the laser, d_b is the beam diameter, and v_w is the relative wind velocity. Expanding this about a typical base case, and using values for a 10.6-μm wavelength, yields the following scaling law:

$$t_c = (3.4\ \text{km})\left(\frac{1\ \text{m/s}}{v_w}\ \frac{0.1\ \text{g/m}^3}{\rho_l}\ \frac{1\ \text{m}}{d_b}\ \frac{P_L}{1\ \text{MW}}\right). \tag{4}$$

Figure 4 shows the predicted penetration vs. laser power, using this equation for a 1-m diameter beam. For convenience, the penetration has been expressed in terms of mm of water if the cloud were collapsed down to a single layer (that is, the thickness is equal to $\rho_l L$). The nominal thickness and range for each cloud type also is shown in the figure. The three solid lines are for relative wind speeds of 1, 10, and 100 m/s.

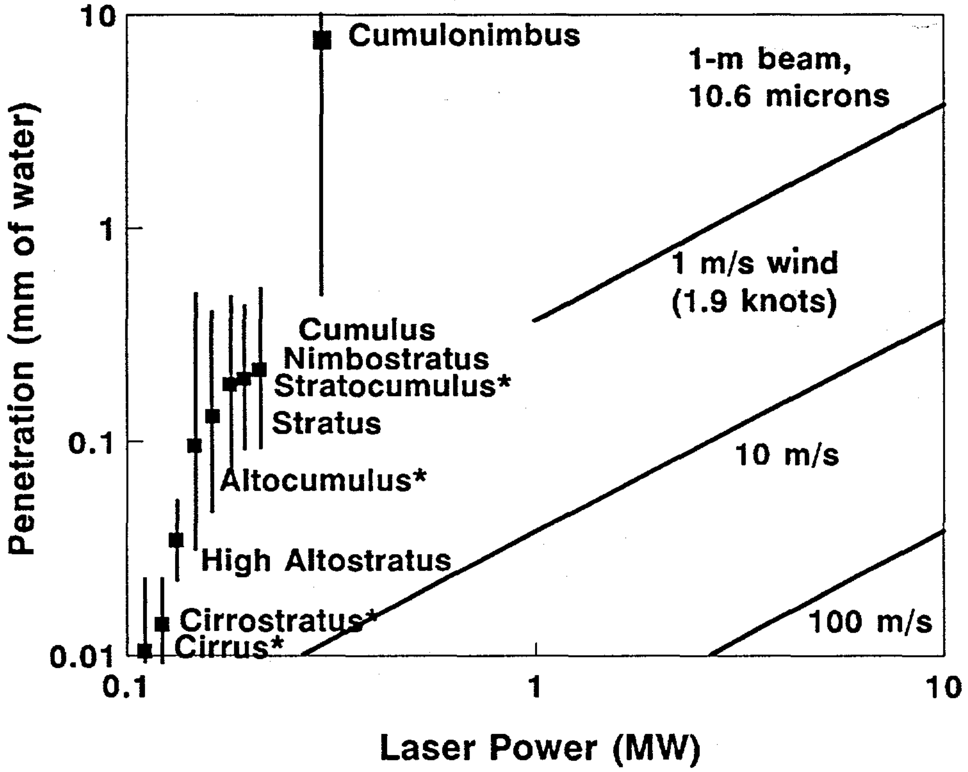

Figure 4. Predicted penetration of clouds vs. laser power for a 1-m diameter beam. Penetration is in terms of collapsed water thickness. The four dominant cloud types at desert sites are shown with asterisks.

There is a wide range in required power due to the large variation in cloud type and wind speed. Power-beaming to LEO is likely to require a beam diameter of about 1 meter, and GEO is likely to require 5 to 10 meters. Table 4 shows the approximate average values for cloud thickness (in mm of liquid water) and wind speed. Also shown are the powers required to clear a 1-m diameter channel. The powers range primarily from 10-70 MW (except for cumulonimbus).

Passing such large powers though a 1-m diameter channel will create optical distortions which may be insurmountable, even with adaptive optics. A good measure of distortion is the optical path difference (OPD) between one part of the channel and the next. The laser beam will probably vary in energy by at least 10% across the channel. The OPD across the channel can be expressed as:

$$\text{OPD} = \Delta T \frac{dn}{dT} L = \left(\frac{\alpha \Delta I t}{\rho_a C_p}\right)\frac{dn}{dT} L, \tag{5}$$

where ΔT is the temperature difference across the channel, dn/dT is the rate of change in the index of refraction with respect to temperature changes, L is the path length over which the temperature difference occurs, α is the absorption coefficient for the laser beam, ΔI is the difference in laser intensity across the channel, t is the duration of the beam, ρ_z is the density of air, and C_p is the specific heat of the air. Consider the OPD in propagation through the first 5 km of the atmosphere. For a 10-MW, 1-m diameter beam with a 10% variation across the channel and a 10-m/s crosswind:[18]

$$\mathrm{OPD} = \left(\frac{(1 \times 10^{-4}\ \mathrm{m^{-1}})(1.2 \times 10^{6}\ \mathrm{W/m^2})(0.1\ \mathrm{s})}{(1.0\ \mathrm{kg/m^3})(1000\ \mathrm{J/kg\,K})} \right) (1.0 \times 10^{-6}\ \mathrm{K^{-1}})\ (5000\ \mathrm{m}) = 60 \times 10^{-6}\ \mathrm{m}. \quad (6)$$

An OPD of 60 μm would be 75 wavelengths at the power-beaming wavelength of 0.8 μm and probably would be impossible for an adaptive optics system to handle. From this we conclude that, for power beaming applications, channels cannot be made in the vast majority of clouds with a ground-based laser beaming directly to satellites. However, there may be some special cases where the nominal crosswind and required power can be reduced.

Table 4. Approximate average values for various clouds and the approximate power needed to clear a 1-m diameter channel. Powers required for a 5-m channel would be 5 times greater.

Cloud	Thickness (mm water)	Altitude (km)	Wind Speed (m/s)	Power Required (1-m channel) (MW)
Ci	0.01	9	30	9
Cs	0.015	7	24	10
As	0.03	6	21	18
Ac	0.10	4	15	43
St	0.15	1	6	26
Sc	0.2	2	9	52
Ns	0.2	3	12	70
Cu	0.2	2	9	52
Cb	9.	5	18	4700

As noted in the introduction, an airborne relay mirror situated on a plane stationed above the laser site has been proposed for some applications. The relay plane would have a capability of about 20 m/s (40 knots) in order to stay near the power beaming site. So it could match speed with the clouds for some period of time. The plane then could fly back upwind for the next run. Unfortunately, if the plane is flying at 25 km altitude at 25 km/s and the cloud is at 8 km altitude, the plane only could match speeds up to 8 m/s with the hole in the cloud because of the lever arm relative to the laser on the ground. So, to utilize this option, it might be necessary to develop a lower-altitude plane with burst-speed capability. If this is done, the relative winds might be reduced to about 10 m/s for most clouds, even when absolute wind conditions are over 20 m/s. With this caveat, Figure 4 suggests that most cirrus and cirrostratus clouds could be handled with a 500-kW laser. With this reduced power level, the OPD over the first 5 km could be as low as only 3 μm with a 10-m/s crosswind for a standard atmosphere, and even less at a desert site. This should be within the capability of adaptive-optic systems. The OPDs from thermal variations within the clouds caused by evaporation of the ice crystals will be less than along the path to the cloud because the total water vapor (after hole-boring) is less.

Overcoming cirrus and cirrostratus clouds would cut the downtime due to weather by a factor of two. This is about equivalent to the benefit of adding a second power-beaming site in a separate weather zone.[17] However, only those missions accessible by an airborne relay mirror could benefit from this. Since beaming to GEO requires a large mirror, this mission would be very difficult with an airborne relay. A better overall solution might be to establish a second power-beaming site in a separate weather cell rather than rely upon hole-boring to overcome some of the weather obstacles.

5. LASER OPTIONS

The ideal wavelength for hole-boring would have very high absorption in liquid water, but very low absorption in vapor water and the rest of the atmosphere. It also would be long enough not to scatter much from liquid droplets, but short enough to avoid diffraction-limited divergence over the typical propagation length of 10-30 km. It also would be fairly readily generated by available lasers. The CO_2 laser at 10.6-μm wavelength meets these criteria nicely, which is why most of the hole-boring research was performed with it. So, one option for implementing hole-boring is to add a separate CO_2 laser to the system. But it would be nice if there were even better alternatives, and especially if the power-beaming wavelength also were suitable for hole-boring.

Hale and Querry[19] report on the absorption lengths in water for visible to midinfrared wavelengths. Unfortunately, there are no absorption bands below 2.5 μm that are stronger than the absorption at 10.6 μm. Since scattering increases with decreasing wavelength, this essentially eliminates the power-beaming wavelength (0.8 μm) as a reasonable option. However, there are absorption bands in liquid water from 2.6 to 3.4 μm and 5.9 to 6.3 μm that are much stronger than at 10.6 μm. Kyle[20] reports on transmission through water vapor and the atmosphere. There are broad transmission windows from 2.9 to 5.0 μm and above 7.5 μm. The lack of a transmission window eliminates the 5.9 to 6.3 μm band, leaving only the 3.0 to 3.4 μm band. Transmission in this band is very wavelength dependent, so the wavelength in this region will need to be chosen carefully. Unfortunately, the wavelengths of the primary high-power lasers already demonstrated (COIL at 1.3 μm, DF at 3.6-4.0 μm, and HF at 2.7 μm) do not fall in this band and so are not suitable for hole boring.

However, a free-electron laser (FEL), with a full spectrum of possible wavelengths from visible through infrared, would be ideal for this application since it could be tuned to precisely the optimum line. An examination of the absorption and transmission data suggests that an optimum line might be 3.17 μm. In addition, if the power-beaming laser (at nominally 0.8 μm) also were an FEL, it could use the same power-supply hardware and optical support equipment as the channel-boring beam and thus reduce expenses.

Another option is a reactor-pumped laser (RPL). Reactor-pumped lasing has been demonstrated at over 40 different wavelengths[21-23] from 0.4 to 10 μm. In this case, different portions of the same reactor could be used to generate the two different beams. But since a reactor-pumped laser is not fully tunable, a fortuitous wavelength for hole-boring would need to be found. One good possibility is the krypton line at 3.07 μm, which has been demonstrated by Russian researchers.[21] This line is close to the peak of the liquid water absorption band, and it is within the potentially good atmospheric transmission band. However, one would need to verify that the atmospheric transmission at that precise wavelength is adequate. So far, the efficiency for generation of this line is low (0.2% intrinsic), but improvements might be made. In addition, new RPL lines are being demonstrated each year.

6. SUMMARY

Hole-boring through clouds with a laser has been proposed as a means to overcome weather constraints on laser power beaming. Extensive modeling and experimentation has been devoted to this area. Unfortunately, the required laser powers for direct beaming to satellites are in the range of 10-100 MW. This is partly due to the large channel diameter needed for beaming and the high wind velocity across the channel. Use of a laser relay mirror above the clouds may allow a narrow beam between a ground-based laser and the relay, and may reduce the crosswind if the plane matches speed with the cloud. Under these conditions, it may be possible to penetrate most cirrus and cirrostratus clouds with a 500-kW CO_2 beam. This would reduce the downtime due to weather by about a factor of 2. However, only those missions accessible with an airborne relay mirror could benefit from this. It may be more effective instead to construct another power-beaming site in a separate weather zone.

Cloud-clearing requires a carefully chosen wavelength that is absorbed in liquid water but penetrates water vapor and the atmosphere. The best lines are around 3.0-3.4 μm and above 10 μm. The 10.6-μm line of a CO_2 laser meets these criteria, so one option is to use a separate high-average-power CO_2 laser for cloud penetration. A high-power FEL would be an excellent hole-boring laser since it could be tuned to the optimum absorption line at 3.17 μm. A reactor-pumped laser at 3.07 μm is another good possibility.

7. ACKNOWLEDGMENTS

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