Using GLAS/ICESAT Data To Derive CFLOS Statistics For The Design Of Future Space-Based Active Optical Remote Sensors

Final Report to the
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(ESTO)

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1. Introduction

As NASA designs future laser based remote sensors for space, the issue of clouds will have a significant impact on both the instrument design as well as its operations plan. While space based passive imagers have provided the community with cloud statistics for several decades, those cloud data have been derived mainly from images with ~ 1 km resolution. Furthermore, in most cases, the accounting for multiple layers of clouds has been hampered by pixel resolution and lack of direct ranging. The 14-day LITE (Laser In-space Technology Experiment) mission in 1994 provided the first opportunity to develop cloud statistics with sampling on the scale of a few 100 meters. More recently, global measurements of aerosol and cloud properties with <70 m sampling resolution have been provided by the Geoscience Laser Altimeter System (GLAS) instrument on-board the Ice, Cloud and land Elevation Satellite (ICESat). GLAS/ICESat was launched in January 2003 with a near circular and 94 degree inclination orbit at an altitude of 600 km. The GLAS laser is a diode pumped Nd: YAG laser with 40 Hz pulse repetition, 75 mJ at 1064 nm and 35 mJ at 532 nm.

In support of its Laser Risk Reduction Program, NASA's Earth Science Technology Office (ESTO) funded a study by Simpson Weather Associates (SWA) to investigate and analyze cloud data from GLAS to construct cloud and cloud penetration statistics that can be used to guide the design of future lidars in space. Specifically, SWA was tasked to look at the following statistics and issues:

- Probability of Cloud Free Line Of Sight (CFLOS) opportunities for a laser beam with a footprint less than 100 meters in diameter cloud-free;
- Probability of multiple level intercepts of clouds; and,
- Probability of contiguous CFLOS for various duration of beam stares and shot integration for a series of trade studies involving energy per pulse and pulse repetition frequency.

These statistics were also to be compared with results and statistics compiled from a very limited data set collected during LITE. The results from previous analysis of the 532nm LITE data (Winker and Emmitt, 1997) showed a ground return was provided approximately 60-65% of the time, which was much more often then existing cloud climatologies based on passive imagers suggested (30-40%). In addition, the LITE data also showed that between 37% and 50% of profiles with cloud returns also provided a surface return. This "cloud plus ground return" has been used by SWA to express cloud porosity for lidar beam dimensions.

Throughout this report there are points at which the options for numerous and unlimited detailed analyses became apparent. Thus, rather than this report being a reference document in itself, we offer examples of what the software package (developed as part of this funded effort) can provide. It is hoped that the reader will feel free to contact SWA with suggested or requested queries that can be executed using the current data sets and the CFLOS statistics software. We have also kept the software general enough to process data from CALIPSO once those data become available.

2. GLAS Data

The first step of the funded research was to acquire the GLAS data from the National Snow and Ice Data Center (NSIDC). Several GLAS data products were obtained including Level 1B GLA07 (Global Backscatter data), Level 2 GLA011 (Global Thin Cloud/Aerosol Optical Depths data) and Level 2 GLA09 (Global Cloud Heights for Multi-layers data). The next step was to develop programs/software to process, read and visualize the data. The backscatter and cloud data were then checked against browse products and images available from the NSIDC as a means of a data quality and software check. While there were several data documentation errors initially encountered, the check was deemed satisfactory.

Most of the results presented in this report are derived from the investigation and analysis of the GLA09 Level 2 Cloud Height data. Initial checks were done with one day's worth of data and then statistics were computed using a week's worth of data (November 1 through November 7) of GLA09 release 22. Towards the end of funded research effort, a update of the GLAS data (release 24) was released to the public. Due to time and funding constraints and the fact that the data is still undergoing extensive testing and analysis, the investigators did not add this data release to the study. While it is hoped that future efforts will utilize the most recent release, we do not expect any significant changes to the statistical conclusions presented in this report.

In the GLA09 data products, cloud layer heights are determined for both the 1064 nm and 532 nm channel of the laser with a maximum of ten cloud layers being reported. The following is a brief summary of the GLA09 data product as described by the NSIDC. More detail on this data product is available from:

http://nsidc.org/data/docs/daac/glas_atmosphere/gla09_records.html.

The fundamental or "full" resolution sampling rate of GLAS is 40 Hz. To obtain increasing levels of sensitivity to clouds (thin), individual shots were accumulated and averaged over three other sampling intervals as shown in Table 1. At 532 nm, the cloud heights in GLA09 were determined at four separate sampling intervals: a 4-second ("low" resolution), 1-second ("medium" resolution), .2-second ("high" resolution) and .025 second (40 Hz "full" resolution, but only available for below 10km). Therefore, for each individual 4-second flight interval, there is ONE low resolution data "profile", FOUR medium resolution data profiles, TWENTY high resolution data profiles and ONE-HUNDRED-SIXTY full resolution data or cloud profiles. Cloud layers for the GLAS09 data were determined using algorithms and thresholds described in Palm et al. (2002). As an example, cloud layers are determined for the high, medium and low resolutions based on the averaging of, respectively, 8, 40 and 160 individual shots. To avoid confusion, throughout the discussion we will refer to these groupings for the low, medium and high resolution as "products" or "packets" to distinguish them from the information obtained with individual shots.

Since sensitivity to clouds increases with shot integration, it is very possible that optically thin cloud layers may be found at the low or medium resolution but not in the higher resolution sampling over the same time or data record. If a cloud is found at the low resolution, a subsequent search is conducted at the medium resolution and so forth down through the high resolutions. The 40 Hz or full resolution cloud search is executed in all instances. At 1064 nm, cloud layers are only searched at the low and medium resolutions. During our research, we focused on all sampling rates. In addition, with the 1994 LITE mission also being conducted at 532 nm wavelength, we especially wanted to look at this wavelength to provide the needed comparisons between the GLAS data and results from LITE. Furthermore, the 532 nm channel is more sensitive to the search for cloud layers.

When making comparisons between statistics derived at differing shot integration intervals, the following must be taken into consideration. The likelihood of cloud detection within the interval is a function of both the degree of threshold sensitivity and the area of regard. The more individual shots averaged together to determine the signal to noise ratio (SNR), the more likely it is that optically thin clouds will be detected. Also, the longer the shot integration interval, the more likely it is that an individual shot or lower resolution product will intercept a cloud.

3. Analysis

Table 2 shows the percentage of all shot integration products that registered a ground return at each resolution for a period of one week. As mentioned previously, for this table and subsequent tables, cloud and/or ground returns for the Low, Medium, High resolution products are determined from algorithms using accumulation of 160, 40, and eight individual full resolution (40 Hz) shots, respectively.

As can be seen from Table 2a, approximately 29% of the individual shots for the full resolution GLAS data reported a ground detection. This increased to about 45% for the High resolution, 59% for the Medium resolution and 74% for the Low resolution products. Based upon the LITE experience, the individual shot statistics seemed rather low and it was thought that a possible reason for these low values could be that, although the individual shots were indeed reaching the ground, there was a problem in the detection of ground over different regions of the Earth's surface (ocean, ice). Table 2b shows the increased percentage of ground detection for land surfaces only (rather then all surfaces). At least 43 % of the individual full resolution shots recorded a ground return. This number increased to almost 85% at low resolution, determined from 160 individual shots over a four second period. The percentages of ground returns, especially for the Medium and High resolution products, compare very favorably with the results from LITE (60-65%).

When interpreting the results from the Low, Medium and High resolution derived products, care must be exercised since there is shot integration and thus the detailed distribution of cloud and ground returns within a data product are unknown. For example, the 73.8% ground returns for the Low resolution data product in Table 2a only means that at least 1 shot out of 160 reached the ground. Thus all one can conclude is that if an instrument is designed to integrate over 25 – 30 km, then a ground return can be expected in 74% of the Low resolution packets. As we see later, the chances of getting a cloud return during the same 25-30km integration is ~80% (see Table 5a) suggesting a high degree of cloud porosity (laser sampling that detects cloud and ground in same sample packet).

Based upon Tables 2a and 2b we can guess that surface returns over water are more problematic than over land. This is expected given the high probability of specular reflections off the water surface that don't favor 180 degree reflected returns. This issue complicates the interpretation of the GLAS data at the full resolution (and somewhat at the High resolution) since the cloud penetration statistics use underlying cloud returns or ground returns as evidence of penetration. Thus, one could argue that the cloud penetration statistics derived from the individual shots only underestimate the porosity. We will mention this issue again when discussing Tables 5a and 5b.

The next statistic we addressed was the percentage of time that the GLAS instrument, according to the cloud algorithms that were used, detected a cloud. According to Table 3, only 35% of the individual shots over all surfaces detected a cloud. This number increased to almost 50% at High resolution. Still, from previous cloud climatologies such as ISCCP and LITE, we know that the global cloud coverage is much higher. As mentioned previously, cloud layers for GLAS are determined from both the 1064 and 532 nm channels for both the Medium and Low resolution products. We computed the percentage for both wavelengths together and for only 532 nm cloud detection, the latter done because it is more sensitive to clouds and more specifically for comparison with previous 532 nm LITE results. As shown in Table 3, the GLAS cloud algorithms detected clouds between 70 and 80% of the time for both the Medium and Low resolution products. In general, and as to be expected, more clouds are detected when more individual shots are integrated to determine if clouds are present within increasing integration times (going from Full resolution down to Low resolution). When considering only the 532 nm channel, however, only 55% of the Medium resolution and almost 80% of the Low resolution data recorded a cloud detection.

Another cloud related statistic important to lidar measurements is the number or percentage of shots that hit clouds but also make it to the surface. This is illustrated in Table 4a for all surface types. According to this one week's worth of data, around 40% of the individual shots hit clouds and also reported a ground return. This increased to close to 50% at Medium resolution and 70% at Low resolution. As shown in Table 4b, these numbers are even higher for shots taken over land. Once again, these numbers for the Medium and Lower resolution products are similar to those determined by LITE (37 to 50%). Please note that these percentages are not based upon the total number of shots taken; just those shots that hit clouds. Thus, Tables 4a and 4b are expressions of cloud porosity as determined for different levels of shot integration.

As mentioned before, care must be taken with interpreting the Full resolution numbers since there is a strong likelihood that a single shot that hits a cloud does not retain enough signal to detect the ground. Thus, all of these GLAS data analyses are footnoted with the recognition that porosity (defined here as a cloud return followed by an underlying cloud return or ground return) is a function of the sensitivity of the lidar. We would expect that as we launch more powerful lasers in the future, the porosity will increase.

Tables 5a and 5b summarize the previous results while providing a little more insight into the relative distribution of cloud and ground returns. Looking at Table 5a, one feature that stands out is the number of individual shots and multi-shot products where clouds are not detected but where the ground is also not reported (the last column). This happens over 50% of the time for the individual shots and over 20% for the High resolution products. Once again, as shown in Table 5b for land only, part of the explanation may indeed be the problem with ground detection over water and ice surfaces. In fact, analyses of shots taken over water only, the number of "no cloud/no ground" returns was 53% compared to the 37% over land (Figure 6)

These "no cloud/no ground" cases for full and High-resolution data are most confounding to a satisfactory climatology of cloud penetration statistics. Given the vertical piecewise manner in which clouds are detected by the GLAS algorithms, it is possible for a physically thick but optically thin layer of cloud to attenuate the signal enough to squelch a detectable ground return and also produce a return that is too weak to be classified as cloud. Another possibility is that no cloud was present but the surface was smooth water and did not provide a direct reflection. Attempts to partition these cases between "cloud w/ground" and "no cloud w/ground" has not been defensible and thus we must await a better data set to address cloud porosity on the single shot level.

However, using the assumption that any GLAS profiles without clouds indicate that a useful level of backscatter was available from the ground (even if the surface wasn't reported due to flat water or a faulty ground return algorithm), we can argue that the ground would be viewable for a more powerful lidar for between 80 to 85% of all individual shots (14.6 % + 14.3% and 51% in Table 5a). This conclusion must be accompanied with the reminder that these results are dependent on the GLAS instrument's Energy Aperture Product (EAP) and efficiencies. However, it is our opinion that the main difference between the GLAS instrument's performance (CFLOS wise) and any future and more sensitive lidar will be primarily realized with the non-cloud (aerosol) returns between and below attenuating cloud layers. While this claim is based upon some assumptions, it is probably one of the most important finding of this study; i.e. **80% of individual laser shots have a reasonable chance of getting a ground return.**

One other statistical feature that SWA was tasked to investigate was the presence of multiple cloud layers determined by the GLAS data and cloud detection algorithms. Tables 7, 8 and 9 present the results for, respectively, the Low, Medium and High-resolution products (only 1 layer is ever reported in the full resolution individual shot data). For example, in Table 9 we see that, when clouds are reported, the GLAS High (~1.5 km) resolution processing algorithms detect a single cloud layer 70 percent of the time and two cloud layers 20 percent of the time. Approximately 10% of the time there were three or four cloud layers detected. When a longer integration distance is used, such as 25 km, the occurrences of three, four or five layers increase to nearly 25% of the time when there is any cloud in the scene (see Table 7). This finding bodes well for those instruments, such as coherent Doppler lidars, that can provide useful (accurate) information from just a few shots hitting clouds.

4. Shot Integration and Trade Studies

For both the selection of different lidar technologies (e.g. coherent and direct detection) and the choice of sampling strategies, an important consideration is the number of shots or even consecutive shots that make it to the ground or to a particular level in the atmosphere over a specified distance (temporal stare). For example, to achieve a specified accuracy of measuring the LOS Doppler shift with a direct detection wind lidar, a certain number of photons will be needed during a period of non-scanning (staring). Starting with a cloud free atmosphere, the instrument specifications (laser energy per pulse, PRF, aperture diameter, etc.) can be determined assuming knowledge of the target medium's backscatter distribution with height. However, to meet the same accuracy requirement in the presence of clouds, the integration time or energy per pulse must be increased. Given that there will be cases where the optical depth and contiguous coverage of cloud will preclude any further measurements regardless of the lidar's capabilities, the design task is to trade vertical coverage (of a useful data product) with "reasonable" lidar enhancements over the "cloud free" design points. More specifically, if it is decided to meet the data accuracy requirement within partly cloudy situations, then a percent coverage needs to be chosen and the EAP increased accordingly (e.g. to meet requirements in a 50% cloud coverage situation, the EAP must be doubled).

In the discussion that follows we assume that direct detection is used to get returns from molecules (backscatter or absorption) and that coherent detection is used to get returns from clouds and aerosols.

There are two ways to provide some guidance on the issue of CFLOS statistics for specific shot integration distances. First, the Low-resolution data product can be used directly for ~25 km integration distances (27 km in this case). Table 5a suggests that 19% of the time a 27 km distance would be cloud free and 25% of the time it would be totally cloud covered. This leaves 55% of the time when there is both cloud and ground in the scene. However, the 25% for totally cloud covered is probably higher than what is reasonable to expect from a more powerful lidar since it would probably take several ground returns to provide sufficient signal to be classed as a ground return. Thus, the 25% may become 15% (just as an example) for another, more capable instrument.

A second approach is to choose several integration distances and examine the Low, Medium and High data products to refine both cloud penetration and CFLOS statistics. Thus, in order to provide some useful data for DIAL, Doppler or lasercom instrument design, we processed the GLAS data for several "integration windows". For example, we posed the questions: What is the likelihood that 100% of all data packets taken along a 75 km line (during a stare) will make it to 15 km altitude; 10 km; 5 km….surface? What about 50% of the shots getting to those altitudes? To develop a set of tables and charts that can be used for the selection of shot integration distances, we processed the GLAS data for a week by analyzing contiguous 75, 50 and 25 km segments for cloud penetration and CFLOS statistics. We sorted the data in the vertical by 1 km bins (100 m below 1 km).

Before presenting the results of the 75, 50 and 25 km contiguous shot segments, the "pass through" and "CFLOS" terminology need to be explained. The term "pass through" (Tables 10-18 and Figures 1-8) denotes statistics based upon the positive answer to the question: "Within the basic data packet, are there returns reported for lower layers including the ground?" For example, if the integration distance is 50 km and the High-resolution data packet is being assessed at 10 km , then the question is asked of 37 contiguous packets. If all answer yes, then that 50km segment is recorded as a case of 100% pass through the 10km level. Note that all that is required for a "pass through" is a lower level return. This means that there could have been cloud detected by some of the 8 individual shots that are integrated to yield a High-resolution packet. Thus the "pass through" statistics tend to belie the amount of cloud that is intercepted by the 8 shots (~1.4 km).

On the other hand, the question may be: "How many of the packets down to 10km arrived without any cloud detection". The answers to this question would form the CFLOS statistics. For example, if the integration distance is 50km and the High resolution data packet is being assessed for 10 km, then the question of no cloud detected down to 10 km is asked 37 times (consecutively). If 50% answers yes, then that 50 km segment is recorded as a case of 50% CFLOS. It must be kept in mind that this test of "no cloud" does not give credit to those cases where, perhaps, only 2 or 3 of the 8 individual shots hit a cloud and the remaining shots were cloud free. Thus the tendency is to understate the cloud free LOS opportunities at the 1.4 km scale.

A major issue in the interpretation of the "pass through" and CFLOS statistics involves the "no cloud/no ground" reports. As shown in Tables 5a and 5b, the number of these reports, on a percentage basis, increase with higher resolution (i.e. less sensitivity per data packet). This is consistent with both the way clouds are "detected" and the lower sensitivity of higher resolution data. The GLAS cloud algorithms break the troposphere into sub layers and test for signals exceeding some threshold above the average for that layer which would indicate a cloud. If the cloud material was optically thin over several of these sub layers (yielding a" no cloud" detection for those individual layers) and yet added up to significant optical depths over the entire tropospheric layer, the GLAS cloud algorithms would not report cloud and there may not be enough signal left to get a useful return off the surface and thus a "no cloud/no ground" binning. Some of the "no cloud/no ground" reports could also be truly no cloud but the surface was water and did not provide a strong return.

The number of "no cloud/no ground" cases for land (excluding ice covered areas, coastlines, sea-ice) verses water (also excluding ice covered areas) for individual shots show that there is still no ground return ~37% of the time (Table 6). At the extreme, the conclusion could be that these cases of no cloud/no ground over land are really "deep layer thin cloud/no ground". If we use the ratio of cloud over land returns to cloud over water returns to predict the no cloud/ground returns over water, we would get 28.2% (42/31*20.8). However, the data indicates that only 15% of the time over water is there a no cloud/ground returning situation. Thus one could estimate that over water, even without clouds detectable by GLAS individual shots, the surface return is too weak to be detected twice as often as expected.

It is beyond the scope of our contract to go back and reprocess the GLAS data to check out these inferences regarding the no cloud/no ground returns. In order to not contaminate the "pass through" and CFLOS statistics, we have eliminated all cases where no cloud/no ground data packets account for more than half of the integration path (25, 50 or 75 km). This omission must be considered in making comparisons between differing resolutions products since the likelihood of the no cloud/no ground cases vary greatly (~ 1% for LOW and 22% for HIGH).

In the following discussion, we develop two sets of tables and graphs that can be used to answer two very different questions. First, we ask how often, for a given sampling distance (75, 50 or 25 km), are there returns below various altitudes. Those returns are from clouds or the ground. This set of statistics may be most useful for an instrument that needs only a few of its attempts to get through clouds to still provide a useful data product. The coherent DWL is an example where the accuracy of the observation is tied to a threshold number of photons (as opposed to direct detection where accuracy scales to the total number of photons). The second question asked is how often, for selected sampling distances, are there CFLOS down to various levels. These CFLOS statistics are of most interest to direct detection performance since accuracy is strongly tied to the number of photons returning and the problems associated with cloud reflectance as a background source of photons.

4.1 "pass through" statistics

To start, Table 10 shows the percentage of time where the High, Medium and Low-resolution products reported the ground or passed through a specific vertical level of the atmosphere for the 532 nm wavelengths over a distance of approximately 75km. This distance translates to close to 54 High resolution,11 Medium resolution and 3 Low-resolution data packets (each combination totaling approximately 450 individual full resolution shots). For example, we can see that 68.5% of the time all 54 high resolution products in a 75 km line sample reported signals below 5 km. This and the following information can also be seen graphically in Figures 1 - 8. As is expected, the more sensitive the product (i.e., summary based upon more individual shots) the greater the likelihood that 11 Medium or 3 Low-resolution products would report more success at penetrating cloudy scenes. *This does not mean that there are more "gaps" in the clouds (over 75 km (for example) just because longer product integration times are used. Rather, it means that longer integration times deny one any insight into probability of gaps in the scene but do allow for more sensitivity to clouds below a given level and the ground.*

Another way to interpret Tables 10 – 18 is to consider the example where the design performance is based upon sampling for 75 km (using 54 High resolution packets) to get a single LOS wind measurement. Assume that, to meet a data requirement, it will be necessary to have at least 50% of the packets get through. Thus Table 12 suggests that this will be the case 42% of the time for the targeted layer below 500m. An extension of the information in Tables 10-18 can be seen in Figures 1 – 8. The figures express probability of "pass through" of selected altitudes at different % of attempts. Using Figure 1 for the case above we can see that if it only takes 10% of the total attempts to make a measurement (as may be case for coherent detection) then we should succeed ~ 60% of the time. **This trade is a very cost effective one and should be considered for an initial baseline for any laser-based sensor.**

Another trade can be examined by asking if performance could be enhanced by a longer integration. The cost or trade-off is fewer independent sample areas (fewer LOS in the case of DWL). We use the High-resolution plots Figures 1, 2 and 3 for 75, 50 and 25 km integration segments respectively. As can be seen, there is no proportional benefit to longer integrations if "pass-through" performance is the defining metric. It may be true that the absolute number of pass-through shots increases with integration distance, but the cost is coverage. This is further evidence that the better trade, bolded above, is to decrease the required success rate by increasing the EAP or selecting a technology with an accuracy dependant upon the number of shots.

One may ask WHy does the success rate for any combination of % pass-through and level not tend towards 80%? Keep in mind that the "pass through" and CFLOS statistics removed the "no cloud / no ground" situations. Thus, if our assumption is that these "no cloud/ no ground" represent thin cloud and or weak surface returns from water, then our penetration statistics based upon the High resolution are understated here.

To illustrate the information content of Figures 1-8, the following case is provided. Assume that the data requirement is for a minimum of 50% coverage at any altitude over the entire troposphere and desires 25km stare resolution with a maximum allowable integration distance of 75km. Assume further that a 25km integration point design has been defined for a direct detection lidar that meets the requirements down to and through 2 km (green lines in Figures 1-8). The task is to determine how to achieve the 50% coverage while maintaining accuracy below .5 km. In Figure 3, the 100% success rate for the unit data packets (in this case High resolution) is met for 2 km. The 100% success rate falls to ~ 25% for .5km (yellow line). There are three choices, increase the integration time (to sample 75km), increase the EAP or employ a technology whose accuracy is mostly dependent upon being above a threshold sensitivity rather than signal strength. If the integration distance is increased to 75 km, the probability of getting pass through actually goes down slightly (~ 5 % for .5 km). However, the 50% objective is almost met with 30% of the 3x the number of attempts in 75km compared with 25km. The other option is to increase the EAP by a factor of 3 so that the 25km performance meets the accuracy requirement. The third option is to use coherent lidar to probe the region below .5 km since its accuracy is only weakly dependent upon the signal strength and this lower portion of the atmosphere usually has the highest aerosol backscatter. This last option would require that the coherent lidar meet the coverage requirements with just 30% of its attempts and thus meet the desired 25km resolution as well.

Similar to the discussion above, we can see from Figures 1-9 and Tables 10, 13 and 16 that, for 100% success below 10 km, there was a general 2-8% decrease across the board for all resolutions when the integration distance was increased from 25 km to 75 km. By studying Tables 10-18 and Figures 1-9 we also see that, as the requirements are lessened to 80% and 50% success rate, we see more and more shots making it through the atmosphere. The comparison of the 75 km and 50km results (primarily at the 80 and 50% success rates) suggests that there is very little change in the percent of time that the products report passing through the various levels in the atmosphere. One interpretation of this finding is that the success rate is more sensitive to the strength of the signal then the integration distance being considered. This may, after further study, be a most significant finding of these initial analyses.

This is further stressed by an analysis that looks only over an integration length of 25 km, which translates to close to 18 high resolution products, 4 medium resolution products and 1 low resolution products (all totaling approximately 150 individual full resolution shots). We can see from Tables 16-18 and Figures 7-8 that, at this shorter distance, the success of getting 100%, 80% or 50% of the products through various levels of the atmosphere increase somewhat but, once again, improved vertical coverage seems to be more a function of product sensitivity rather than integration distance. Another way of expressing this suggestion is that more is gained by doubling the EAP of a lidar than doubling the integration time if vertical coverage is being considered in cloudy scenes.

4.2 CFLOS statistics

While the "pass through" statistics may be of more value to the design of a coherent detection lidar, the CFLOS statistics are more useful to the design of direct detection lidars. This is especially true for direct detection lidars that employ integration on a chip. The quantum efficiencies of the chip based receivers are ~ 80%, which is 2-5 times more efficient than APDs. The disadvantage of this approach is that a single return from a cloud introduces a bias (non-correctable) in the integration. Thus, the trade is to integrate long enough to get a good SNR and yet short enough to allow cloud-contaminated samples to be flagged.

The CFLOS statistics are presented in Tables 19-27 and Figures 9 – 16. As it was for the "pass-through" statistics, the comparison between various integration packets (Low, Medium and High) must be done with great care since the no cloud/no ground situations vary between these products. For example, one would expect that the probability of getting CFLOS to 500 m would decrease as the shot packet resolution decreased (integration distance increased). Thus the probability of 100% CFLOS to 500 m over 50 km using Low Resolution packets(two of them) should be lower than for High resolution packets (37 of them). However, examination of Table 22 shows that the success rate for two Low packets is 31.6% and 13.4% for High packets. This reversal of ranking is almost certainly due to the removal of more no cloud/no ground cases for the High-resolution case as compared to the Low-resolution case. Consequently, care must be taken when comparing results with differing resolution packets.

The following example is given to illustrate how the CFLOS statistics can be used in the design of a space-based lidar. Suppose that the initial engineering model suggested that a specific EAP would yield a data product that met accuracy specifications given a cloud free atmosphere. The designed called for integration over 50 km and the required vertical coverage was 50% of the globe down to 500 meters. Looking at the Low-resolution column in Table 22, it appears that all 160 shots get to 500 meters only 31.6% of the time. Since that represents only 27.2 km (Table 1), we can use Figure 16 to illustrate that the probability of two contiguous LOW resolution packets getting to 500 meters totally cloud free (CF) is only ~30%. The issue thus is how many shots in a 320 shot sequence are likely to get to 500 meters at least 50% of the time. Extrapolating from the LOW resolution data in Tables 23 and 24, we might expect the probability to be ~ 30% of the shots getting to 500m CF 50% of the time if 50 km integration is used. This would mean that the EAP would need to be tripled over that determined from the cloud free engineering model prediction.

Another approach would be to ask what the benefits of using shorter integration intervals might be. The answer is we can't use the GLAS data directly in this case due to the "no cloud/no ground" problem. Instead we can use Figure 13 to see if we can obtain some insight to how to meet the 500 m coverage/accuracy requirement. If we assume that the slope of the yellow line in the figure is reasonable and that the CFLOS statistics using Medium resolution packets should converge with the Low resolution packet statistics at 100% CFLOS (i.e. if there are no clouds detected by the higher sensitivity Low resolution processing , then there should not be any detected by the Medium resolution processing) then we could conclude that only 10-20% of the Medium shot packets get to 500 meters 50 % of the time. In this case, one would need to increase the EAP by a factor of 5-10.

The examples above illustrate how the GLAS data can provide some insight to the likelihood of CFLOS scenes for direct detection shot integration. However, the problem associated with the GLAS "no cloud/no ground" cases precludes us from being very specific. It is very likely that the data from the new cloud satellites now in orbit (CALIPSO and CLOUD-SAT) will allow us to be more precise in defining these CFLOS opportunities.

5. Summary of Results

Various cloud statistics were computed for a full week's worth of GLAS09 cloud data. This included statistics relating to ground detection, cloud detection, CFLOS and multiple cloud layers. The statistics were calculated for the individual shots (40 Hz) and three other multi-shot integration products: High resolution (8 shots), Medium resolution(40 shots) and Low resolution(160 shots).

The data suggests that at least 43% and perhaps as high as 80% of the individual shots made it to the ground. Similarly, between 57% and 85% of the other resolution products made it to the ground. This, especially the medium resolution, compared favorably with previous results from LITE (60-65%). Given our interpretation of the "no cloud/no ground" cases, the higher percentage of full tropospheric penetration is more likely.

We also investigated CFLOS and found that 65% of all individual shots did not detect a cloud. However, when the other sampling segments (where individual shots were averaged) were considered, it was shown that the CFLOS decreased to approximately 50% for the High resolution and 20-40% (depending on the channel) for the Medium and Low-resolution segments. In summary, it was shown as expected that the Lower resolution was more sensitive to clouds, represented higher spatial sampling and thus detected a higher percentage of clouds.

Going a step further, we also looked at the percentage of individual shots or multi-shot products that hit clouds and also made it to the surface. This was true for 40% of the individual shots. Even higher percentages were found for the Medium (50%) and Low (70%) resolution products, with the numbers for the Medium resolution packets found to be similar to LITE results (60-65%).

In total, when looking at the cloud and ground detection statistics, it was determined that between 70 and 85% of all shot products, regardless of resolution, provided access to the entire tropospheric column. This does not suggest that there would be enough signals from the non-cloud aerosols for useful data products, but it does suggest that the porosity of the clouds far exceeds that which might be suggested by a general statement of 70 to 80 % global cloud coverage by current cloud climatologies.

Another feature that was investigated was the presence of multiple cloud layers. From this one week's worth of GLAS cloud data, it was found that, when cloud layers were detected, there was one cloud layer 60-70% of the time and two cloud layers (at different levels) around 20% of the time. Three or four cloud layers were found between 5 and 10% of the time. This was true for all sampling resolutions.

A series of trade studies based on shot integration length and sampling/staring strategies was also conducted with the hope of providing information beneficial to the design of current and future space-based lidar technologies. As an example, it was found that, over a 75 km integration distance, 98% of the time ALL (100% success rate) individual High resolution packets reported returns below 15 km. However, only 19% of the time did ALL products make it below 500 meters. For 500 m, this latter number increased to 30% of the time and 43% of the time for, respectively, an 80% and 50% success rate.

Similar analysis was done for two shorter integration distances, 50 km and 25 km. When decreasing the integration distance from 75 km to 50 km, we saw a 2-8% increase in the percent of time where ALL products passed through. This was true for most levels and all resolutions. A subsequent 2-6% increase was also seen when the integration distance was decreased from 50 km to 25 km. However, as with the 75 km trade study, there are significant increases in the percentage of time that 80% and 50% of all products passed through a given level. These features lend one to consider that energy considerations might have a bigger impact then the integration distance.

6. Conclusions

Analysis of GLAS cloud data was used to investigate the following issues:

- Cloud interception statistics (closely related to cloud coverage),
- Multiple cloud layer visibility by lidar beams,
- Ground detection statistics (suggesting aerosol detection opportunities along the entire LOS), and
- Example trade studies involving energy/pulse, integration times and vertical coverage.

For total cloud coverage, the GLAS data has revealed global total cloud values (~80%), which are very close to, those found with a small set of data from LITE. These values are higher than values determined from ISCCP, suggesting that active optical remote sensing is revealing higher cloudiness. Perhaps this difference is insignificant given the types of data involved, but the sense is that the more sensitive and higher resolution active sensors will continue to sense more cloud than in the past. Even with the new AIRS, the issue of cloud contamination has become more acute with higher sensor sensitivity and resolution. It is noteworthy that the GLAS instrument is of very modest sensitivity compared to the recently launched CALIPSO and future DIAL and Doppler lidars.

An advantage of lidar cloud detection is the ability to detect multiple layers of clouds and to provide information on the physical and optical thicknesses of the layers. In the case of GLAS, two layers of clouds were detected over 40% of the time based upon the more sensitive Low resolution product but only 20-25% at the High resolution. This bodes well for instruments using aerosol detection for winds since the signal from clouds should be strong enough for accurate measurements within the cloudy layers given that the instrument will probably be designed for the lower backscatter from aerosols.

The presence of a ground return in the GLAS data is evidence that the GLAS instrument had sufficient transmitted energy to get a return under the given circumstances. A more sensitive instrument may get more ground returns; a weaker instrument, fewer returns. Thus, generalizations must be considered with caution. By the same token, the absence of a ground return in the GLAS data does not mean the lidar beam did not arrive at the surface with insufficient energy to provide a backscattered return from a favorable ground cover. The surface might have been smooth, mirror like water or the ground detection algorithm may have failed. Thus the % of shots with ground returns is probably understated in our analyses. Using the most sensitive product (Low resolution), we find ground returns 75% of the time over all surfaces and 84% of the time over land. Based upon the individual shot data, the percentage of shots with a ground return over land was 43%. This number could be as high as 80% if we assume that the “no cloud/no ground” cases are really ground viewable cases with either thin cloud or water surface. This also makes sense since the Low resolution product summarizes the returns over a ~28 km line of 160 shots and thus has a higher probability of reporting a surface return over that of individual shots.

The primary utility of the GLAS data is in the specification of the integration interval necessary for achieving target measurement accuracy in the presence of clouds. In some cases, the instrument trade may involve trading greater energy per pulse for a lower pulse rate, simply having to increase the overall EAP to get sufficient return over less time (shorter integration distances). In the case of direct detection, the performance of the system is usually directly scaled to the number of photons used in the measurement. When multiple shot integration is required to obtain the needed photon count, the question is then "How often do clouds preclude getting the required photon count?" Another way to ask that question is "What are the probabilities of getting the required number of individual shots through to various levels of the atmosphere when clouds are in the target area?" While there are unlimited variations on the choice of target integration times and signal return requirements, we chose three scenarios to illustrate the utility of the GLAS data. In general we can make a few summary statements:

1. Clouds in a Lidar LOS are the rule (~ 80%). Whether the cloud is detected and penetrated depends upon the lidar's capability and the optical depth of the cloud. The lidar's sensitivity to optically thin clouds and aerosols can be improved by shot integration. However, reliable shot integration can be frustrated by cloud cover variation within targeted sampling windows.
2. In cloudy situations, the longer the integration time (distance) the less likely all shots will reach a target layer beneath clouds. However, the success rate does not scale linearly to the integration distance. For example, going from 80% success at 75 km may only improve by a few % by going to 25 km integration.
3. The data suggest that more vertical coverage is gained by increasing the sensitivity of the lidar (higher EAP) rather than increasing the integration time (distance).

Given that the GLAS data is now processed with software designed to address question unique to space-based lidar atmospheric /ground coverage, it is hoped that instrument designers will propose more specific trade studies that impact both the design as well as the operation of future lidars.

7. References

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Winker, D. M. and G. D. Emmitt, 1997: Relevance of Cloud Statistics Derived from LITE Data to Future DOPPLER Wind Lidars, 9th Conference on Coherent Laser Radar, June 23-27, 1997, Linkoping, Sweden, 144-147.

G.D. Emmitt and G. Séze, 1991: Clear line of sight (CLOS) statistics within cloudy regions and optimal sampling strategies for space-based lidars. Proc. AMS Seventh Symp. on Meteor. Observa. and Instru., New Orleans, LA, January 14-18, 440-442.

TABLES

Table 1: Sampling resolutions of the GLAS cloud data product.

Product Name	# shots averaged	Horizontal Resolution (km)*	Vertical Resolution (m)
Low	160	27.2	~70
Medium	40	6.8	~70
High	8	1.36	~70
Full	1	.170	~70

* assumes 6.8 km/sec orbit speed

Table 2a: Percentage of shot products that hit the ground over the course of one week of GLAS observations over all surfaces.

	Number	Percent with Ground Detection
Low Resolution	142072	73.8%
Medium Resolution	568288	58.7%
High Resolution	2841440	44.7%
Full Resolution	22731520	28.8%

Table 2b: Percentage of shot products that hit the ground over the course of one week of GLAS observations over land.

	Number	Percent with Ground Detection
Low Resolution	27194	84.7%
Medium Resolution	108776	72.8%
High Resolution	543880	57.1%
Full Resolution	4351040	42.7%

Table 3a: Percentage of shot products that hit cloud over the course of one week of GLAS observations over all surfaces.

	Number	**Percent with Cloud Detection**
Low Resolution	142072	80.0%
Low Resolution (532 only)	142072	79.9%
Medium Resolution	568288	73.2%
Medium Resolution (532 only)	568288	55.2%
High Resolution	2841440	49.1%
Full Resolution	22731520	34.7%

Table 3b: Percentage of shot products that hit cloud over the course of one week of GLAS observations over land.

	Number	**Percent with Cloud Detection**
Low Resolution	27194	66.7%
Low Resolution (532 only)	27194	66.3%
Medium Resolution	108776	61.4%
Medium Resolution (532 only)	108776	53.5%
High Resolution	5433880	47.3%
Full Resolution	4351040	42.1%

Table 4a: Percentage of shot products that hit cloud and also hit ground over all surfaces

	Number	**Cloud with Ground Detection (Percent)**
Low Resolution	113717	68.8%
Low Resolution (532 only)	113449	68.7%
Medium Resolution	415727	49.5%
Medium Resolution (532 only)	313694	48.4%
High Resolution	1394073	33.3%
Full Resolution	7886760	41.9%

Table 4b: Percentage of shot products that hit cloud and also hit ground over land surfaces.

	Number	Cloud with Ground Detection (Percent)
Low Resolution	18143	77.2%
Low Resolution (532 only)	18051	77.1%
Medium Resolution	66751	58.0%
Medium Resolution (532 only)	58148	56.3%
High Resolution	257420	36.7%
Full Resolution	1831866	52.0%

Table 5a: Percentage breakdown of all shot products over all surfaces

Resolution	Cloud and Ground	Cloud and No Ground	No Cloud and Ground	No Cloud and No Ground
Low	55.0%	25.0%	18.7%	1.3%
Low (532 only)	54.9%	25.0%	18.9%	1.2%
Medium	36.2%	37.0%	22.5%	4.3%
Medium (532 only)	26.7%	28.5%	32.0%	12.9%
High	15.8%	33.2%	28.8%	22.2%
Full	14.6%	20.1%	14.3%	51.0%

Table 5b: Percentage breakdown of all shot products over land

Resolution	Cloud and Ground	Cloud and No Ground	No Cloud and Ground	No Cloud and No Ground
Low	51.5%	15.2%	33.2%	0.1%
Low (532 only)	51.2%	15.2%	33.5%	0.1%
Medium	35.6%	25.8%	37.2%	1.4%
Medium (532 only)	30.0%	23.4%	42.7%	3.9%
High	17.4%	30.0%	39.8%	12.8%
Full	21.9%	20.2%	20.8%	37.0%

Table 6: Comparison of cloud and surface detection over water vs. land using the High resolution data packets.

Surface	Cloud w/ ground	Cloud w/ no ground	No cloud w/ ground	No cloud/no ground
Land	21.9%	20.2%	20.8%	37.0%
Water	9.2%	23.1%	15.0%	52.7%

Table 7: Number of cloud layers (percentage) when clouds are detected for the Low resolution product

Number of cloud layers	Low (all surfaces)	Low (land)	Low – 532 (all surfaces)	Low – 532 (land)
0 (only 1064 nm layers)			27.7	14.7
1	24.5	16.1	51.8	55.5
2	48.1	48.1	14.9	21.7
3	13.3	15.7	4.3	6.2
4	9.2	13.0	1.0	1.5
5	3.0	4.3	0.2	0.3
6	1.4	1.8	0.04	0.04
7	0.4	0.7	0.006	0.005
8	0.13	0.2	0.005	0.004
9	0.06	0.06	0	0
10	0.01	0.01	0	0

Table 8: Number of cloud layers (percentage) when clouds are detected for the Medium resolution product.

Number of cloud layers	Medium (all surfaces)	Medium (land)	Med. - 532 (all surfaces)	Med – 532 (land)
0 (only 1064 nm layers)			7.2	7.2
1	35.6	25.7	65.7	59.5
2	40.4	41.7	18.2	22.7
3	13.2	17.3	6.3	7.8
4	6.7	9.6	1.9	2.1
5	2.7	3.8	0.5	0.5
6	1.0	1.3	0.1	0.1
7	0.2	0.4	0.01	0.01
8	0.07	0.1	0.003	0.003
9	0.001	0.001	0	0
10	0	0	0	0

Table 9: Number of cloud layers (percentage) when clouds are detected for the High resolution product.

Number of cloud layers	High (all surfaces)	High (land surfaces)
1	70.7	64.2
2	19.4	24.2
3	6.9	8.3
4	2.2	2.4
5	0.6	0.6
6	0.2	0.2
7	0.03	0.03
8	0.002	0.001
9	0	0
10	0.	0

Table 10: Percentage of time where all (100%) of the shot products passed through a given altitude over a ~75 km distance.

Altitude (m)	Low (532)	Medium (532)	High
> 15000	99.3	99.1	98.1
10000	96.8	94.8	87.6
5000	88.5	82.0	68.5
3000	83.0	73.6	56.0
2000	77.0	64.5	40.6
500	65.4	44.1	19.3

Table 11: Percentage of time where 80% of the shot products passed through a given altitude over a ~75 km distance

Altitude (m)	Low (532)	Medium (532)	High
> 15000	99.3	99.6	99.3
10000	96.8	96.4	93.2
5000	88.5	87.2	79.1
3000	83.0	80.3	68.5
2000	77.0	72.4	57.3
500	65.4	53.7	30.0

Table 12: Percentage of time where 50% of the shot products passed through a given altitude over a ~75 km distance

Altitude (m)	Low (532)	Medium (532)	High
> 15000	99.9	99.9	99.9
10000	98.4	97.8	96.1
5000	93.4	91.1	86.6
3000	89.5	86.0	77.7
2000	85.5	80.2	68.8
500	77.3	64.9	42.2

Table 13: Percentage of time where all (100%) of the shot products passed through a given altitude over a ~50 km distance.

Altitude (m)	Low (532)	Mid (532)	High
> 15000	99.5	99.3	98.4
10000	97.3	95.6	89.4
5000	90.3	84.2	72.0
3000	85.2	76.1	59.4
2000	79.9	67.5	44.3
500	69.1	47.6	21.9

Table 14: Percentage of time where 80% of the shot products passed through a given altitude over a ~50 km distance

Altitude (m)	Low (532)	Mid (532)	High
> 15000	99.5	99.6	99.3
10000	97.3	96.5	93.9
5000	90.3	87.0	80.7
3000	85.2	80.1	70.2
2000	79.9	72.4	59.4
500	69.1	54.2	32.4

Table 15: Percentage of time where 50% of the shot products passed through a given altitude over a ~50 km distance

Altitude (m)	Low (532)	Mid (532)	High
> 15000	99.9	99.8	99.8
10000	99.0	97.7	96.3
5000	95.0	90.7	86.9
3000	91.0	85.6	78.2
2000	89.1	79.3	69.3
500	82.7	64.1	43.5

Table 16: Percentage of time where all (100%) of the shot products passed through a given altitude over a ~25 km distance

Altitude (m)	Low (532)	Mid (532)	High
> 15000		99.6	98.9
10000		96.5	91.8
5000		86.7	76.6
3000		79.6	64.9
200		71.2	51.0
500		52.9	27.2

Table 17: Percentage of time where 80% of the shot products passed through a given altitude over a ~25 km distance

Altitude (m)	Low (532)	Mid (532)	High
> 15000		99.6	99.4
10000		96.5	94.5
5000		86.7	82.1
3000		79.6	72.4
2000		71.3	61.5
500		52.9	35.1

Table 18: Percentage of time where 50% of the shot products passed through a given altitude over a ~25 km distance

Altitude (m)	Low (532)	Mid (532)	High
> 15000		99.9	99.8
10000		98.1	96.7
5000		91.9	87.3
3000		86.7	79.1
2000		80.8	45.7
500		66.8	35.7

Table 19: Percentage of time where all (100%) of the shot products had a CFLOS down to a given altitude over a ~75 km distance.

Altitude (m)	Low (532)	Medium (532)	High
> 15000	96.9	96.8	95.2
10000	83.5	82.3	76.3
5000	61.8	60.7	50.7
3000	53.9	52.9	41.4
2000	44.5	44.2	29.5
500	24.3	22.8	11.0

Table 20: Percentage of time where 80% of the shot products had a CFLOS down to a given altitude over a ~75 km distance

Altitude (m)	Low (532)	Medium (532)	High
> 15000	96.9	98.0	97.4
10000	83.5	86.4	81.7
5000	61.8	66.0	57.3
3000	53.9	58.3	47.7
2000	44.5	50.2	38.7
500	24.3	27.8	14.2

Table 21: Percentage of time where 50% of the shot products had a CFLOS down to a given altitude over a ~75 km distance

Altitude (m)	**Low (532)**	**Medium (532)**	**High**
> 15000	98.1	98.7	98.4
10000	88.0	89.3	86.0
5000	70.3	71.9	63.9
3000	63.2	64.2	54.0
2000	56.0	57.5	46.1
500	36.5	35.7	20.6

Table 22: Percentage of time where all (100%) of the shot products had a CFLOS down to a given altitude over a ~50 km distance.

Altitude (m)	**Low (532)**	**Mid (532)**	**High**
> 15000	97.4	97.4	95.9
10000	85.6	84.6	78.7
5000	66.3	63.7	54.3
3000	59.1	55.9	44.8
2000	50.8	47.2	32.5
500	31.6	25.6	13.4

Table 23: Percentage of time where 80% of the shot products had a CFLOS down to a given altitude over a ~50 km distance

Altitude (m)	**Low (532)**	**Mid (532)**	**High**
> 15000	97.4	98.0	97.5
10000	85.6	86.7	82.9
5000	66.3	67.0	59.7
3000	59.0	59.0	50.1
2000	50.8	50.5	41.1
500	31.6	28.8	16.7

Table 24: Percentage of time where 50% of the shot products had a CFLOS down to a given altitude over a ~50 km distance

Altitude (m)	**Low (532)**	**Mid (532)**	**High**
> 15000	98.5	98.7	98.4
10000	90.4	89.6	86.6
1000	74.8	72.3	65.3
3000	68.4	64.7	55.6
2000	61.9	57.3	47.4
500	44.8	36.2	22.2

Table 25: Percentage of time where all (100%) of the shot products had a CFLOS down to a given altitude over a ~25 km distance

Altitude (m)	**Low (532)**	**Mid (532)**	**High**
> 15000		98.0	96.8
10000		87.3	82.6
5000		68.8	60.4
3000		61.2	50.8
2000		53.0	38.8
500		32.9	18.1

Table 26: Percentage of time where 80% of the shot products had a CFLOS down to a given altitude over a ~25 km distance

Altitude (m)	**Low (532)**	**Mid (532)**	**High**
> 15000		98.0	97.8
10000		87.3	84.8
5000		68.8	63.3
3000		61.2	53.8
2000		53.0	44.6
500		32.9	20.5

Table 27: Percentage of time where 50% of the shot products had a CFLOS down to a given altitude over a ~25 km distance

Altitude (m)	Low (532)	Mid (532)	High
> 15000		98.9	98.6
10000		90.8	87.8
5000		74.7	67.8
3000		67.0	58.3
2000		59.7	49.9
500		38.3	25.0

FIGURES

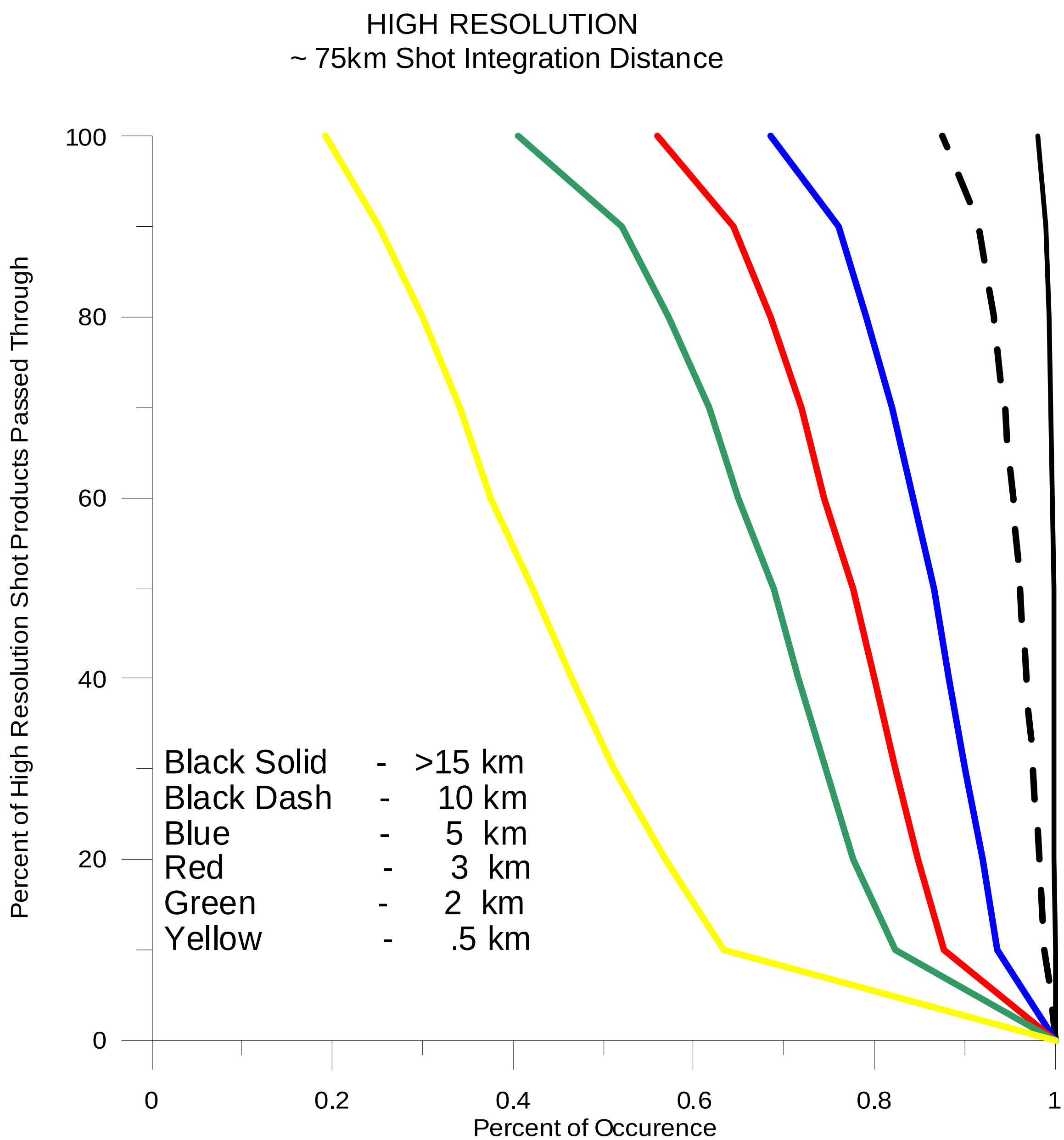

Figure 1: Percent of time various percentages of High resolution shot products passed through different levels of the atmosphere for an integration length of ~ 75 km.

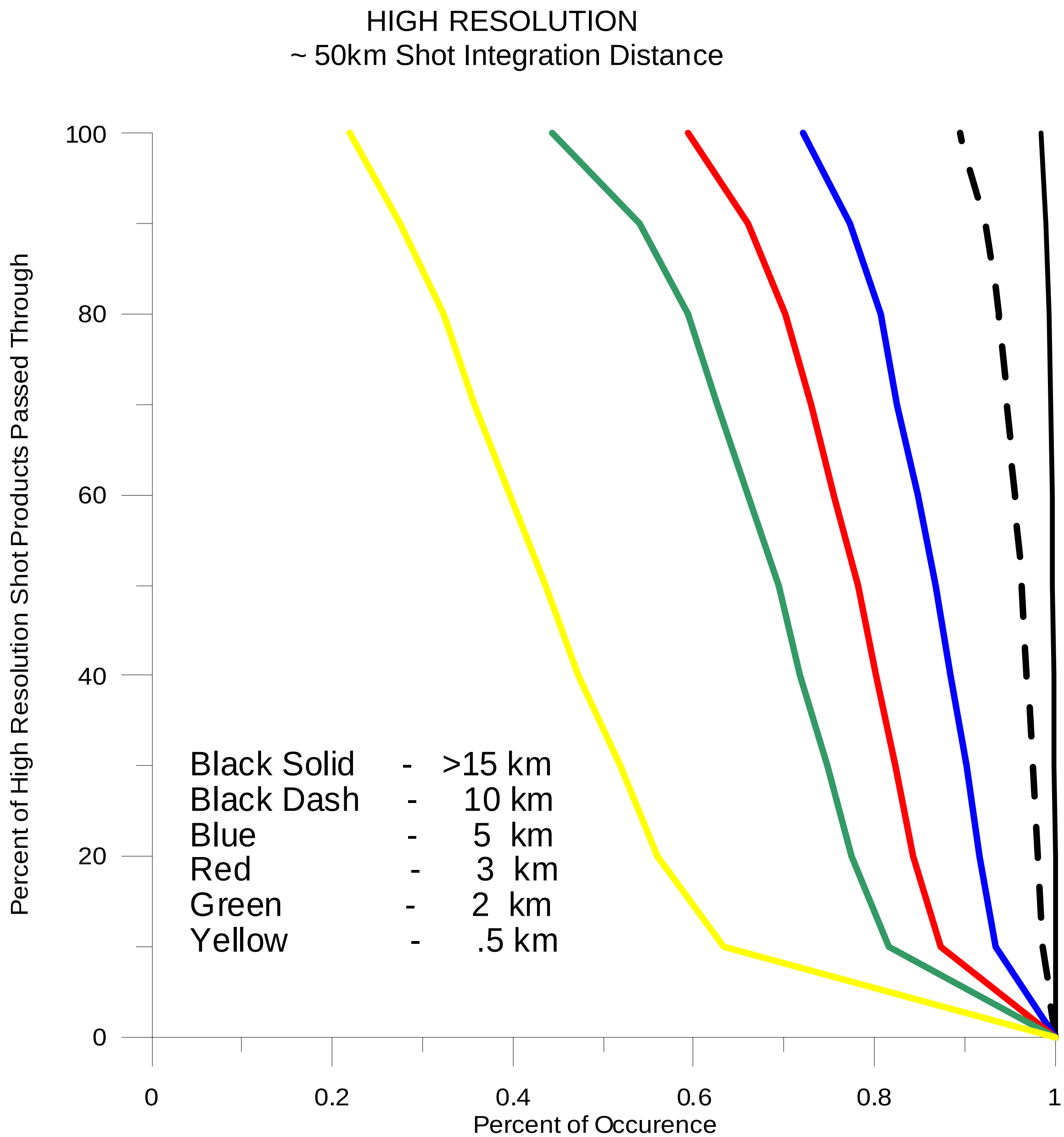

Figure 2: Percent of time various percentages of High resolution shot products passed through different levels of the atmosphere for an integration length of ~ 50 km.

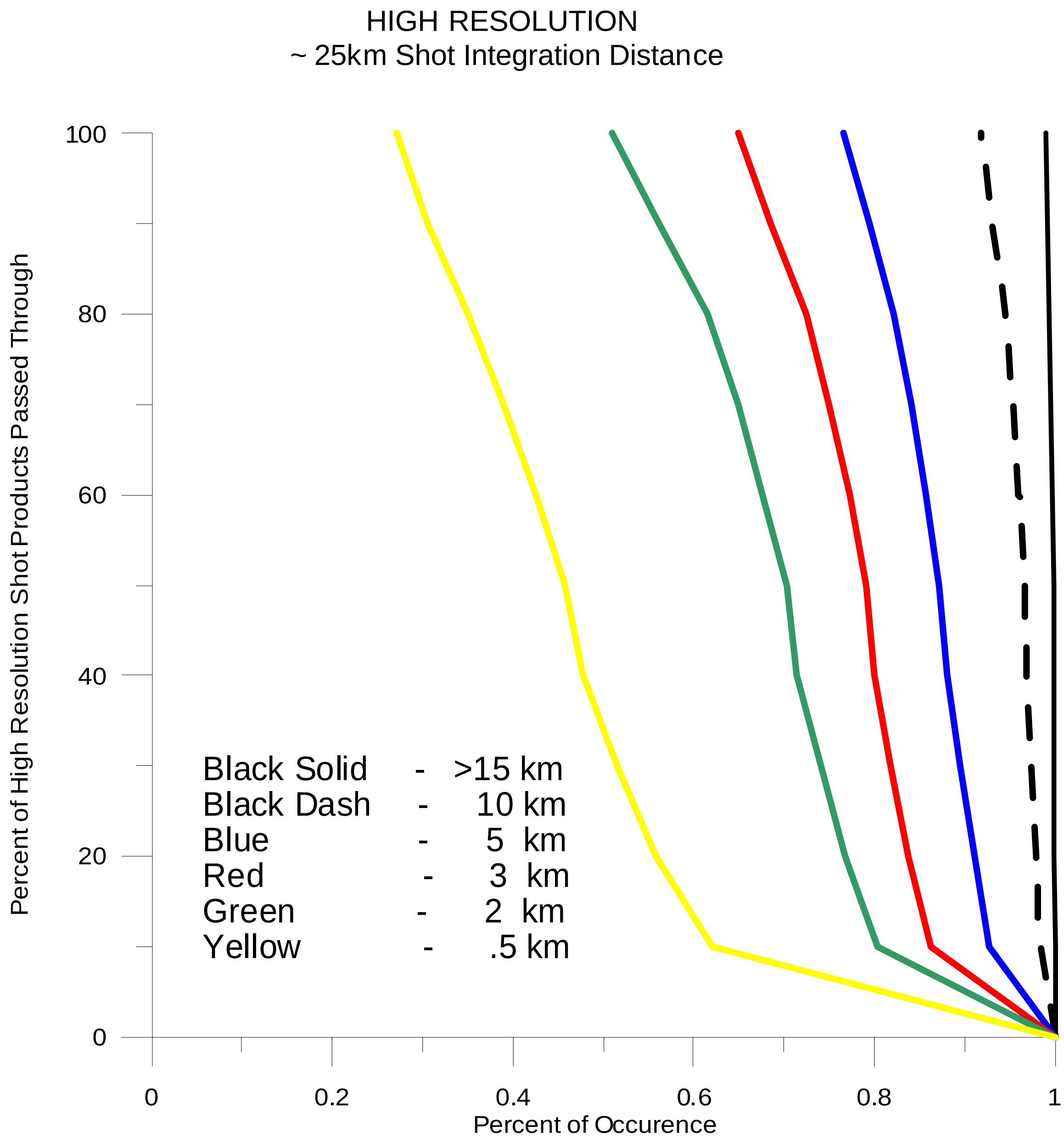

Figure 3: Percent of time various percentages of High resolution shot products passed through different levels of the atmosphere for an integration length of ~ 25 km.

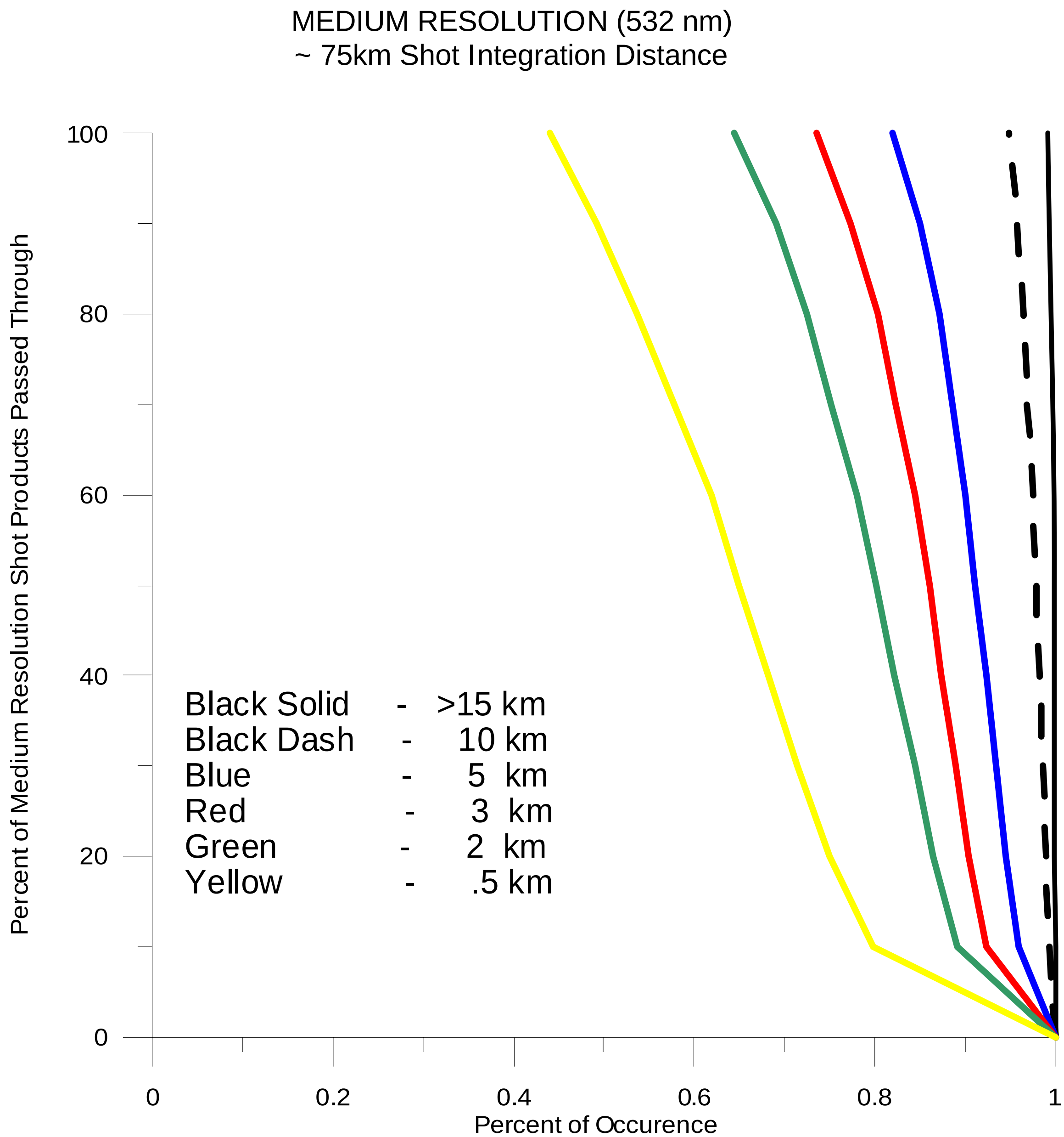

Figure 4: Percent of time various percentages of Medium resolution (532 nm) shot products passed through different levels of the atmosphere for an integration length of ~ 75 km.

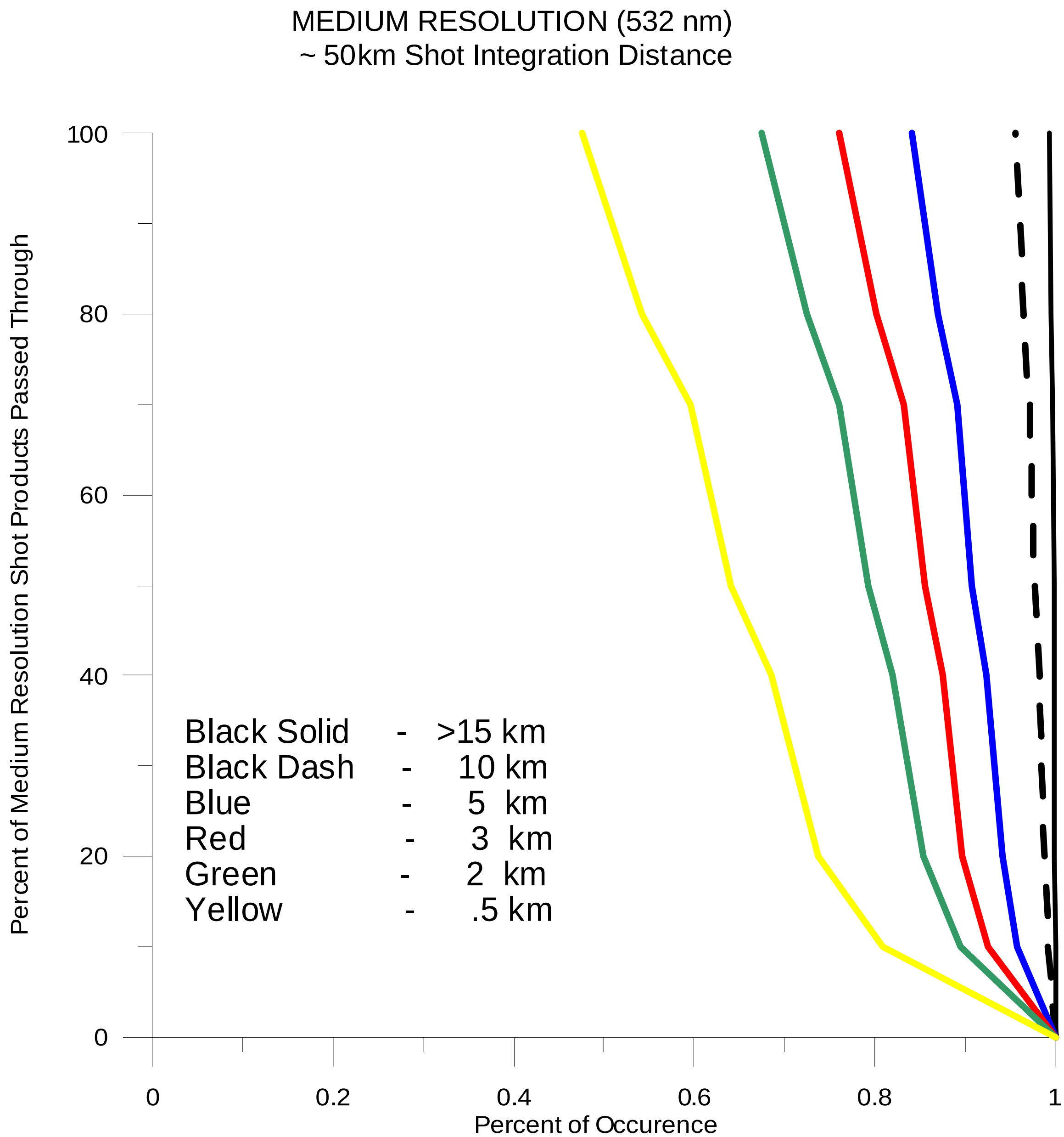

Figure 5: Percent of time various percentages of Medium resolution (532 nm) shot products passed through different levels of the atmosphere for an integration length of ~ 50 km.

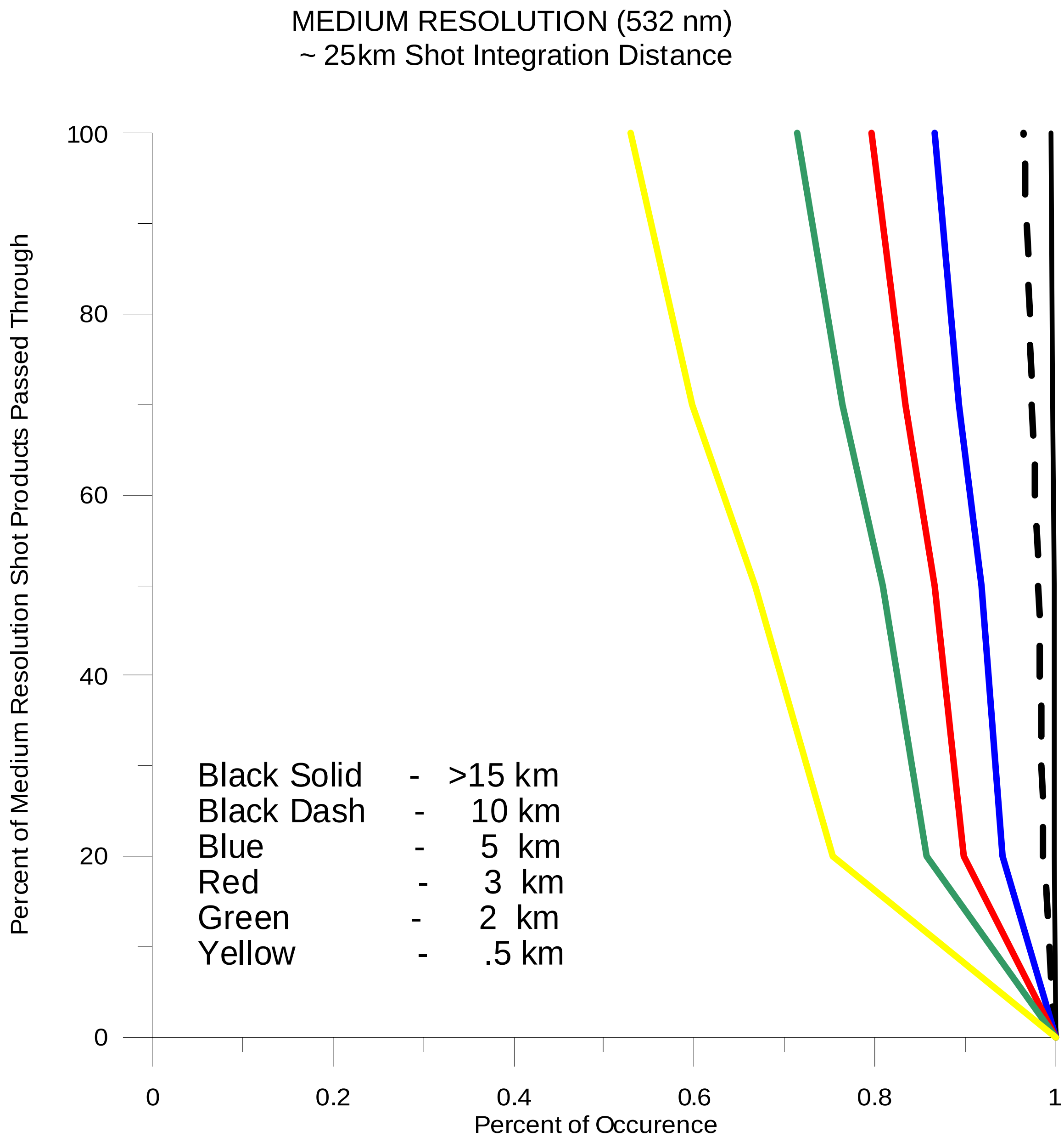

Figure 6: Percent of time various percentages of Medium resolution (532 nm) shot products passed through different levels of the atmosphere for an integration length of ~ 25 km.

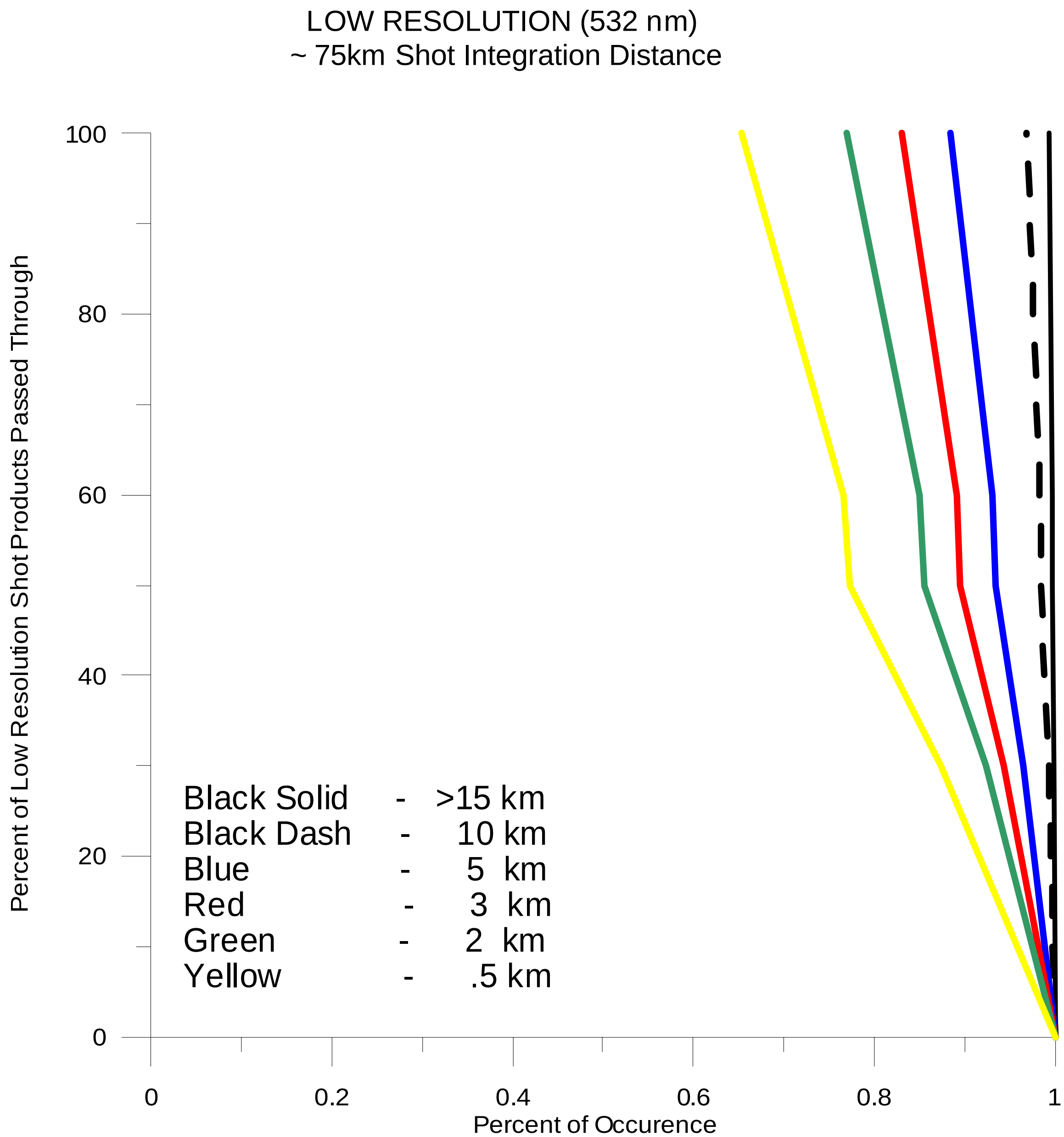

Figure 7: Percent of time various percentages of Low resolution (532 nm) shot products passed through different levels of the atmosphere for an integration length of ~ 75 km.

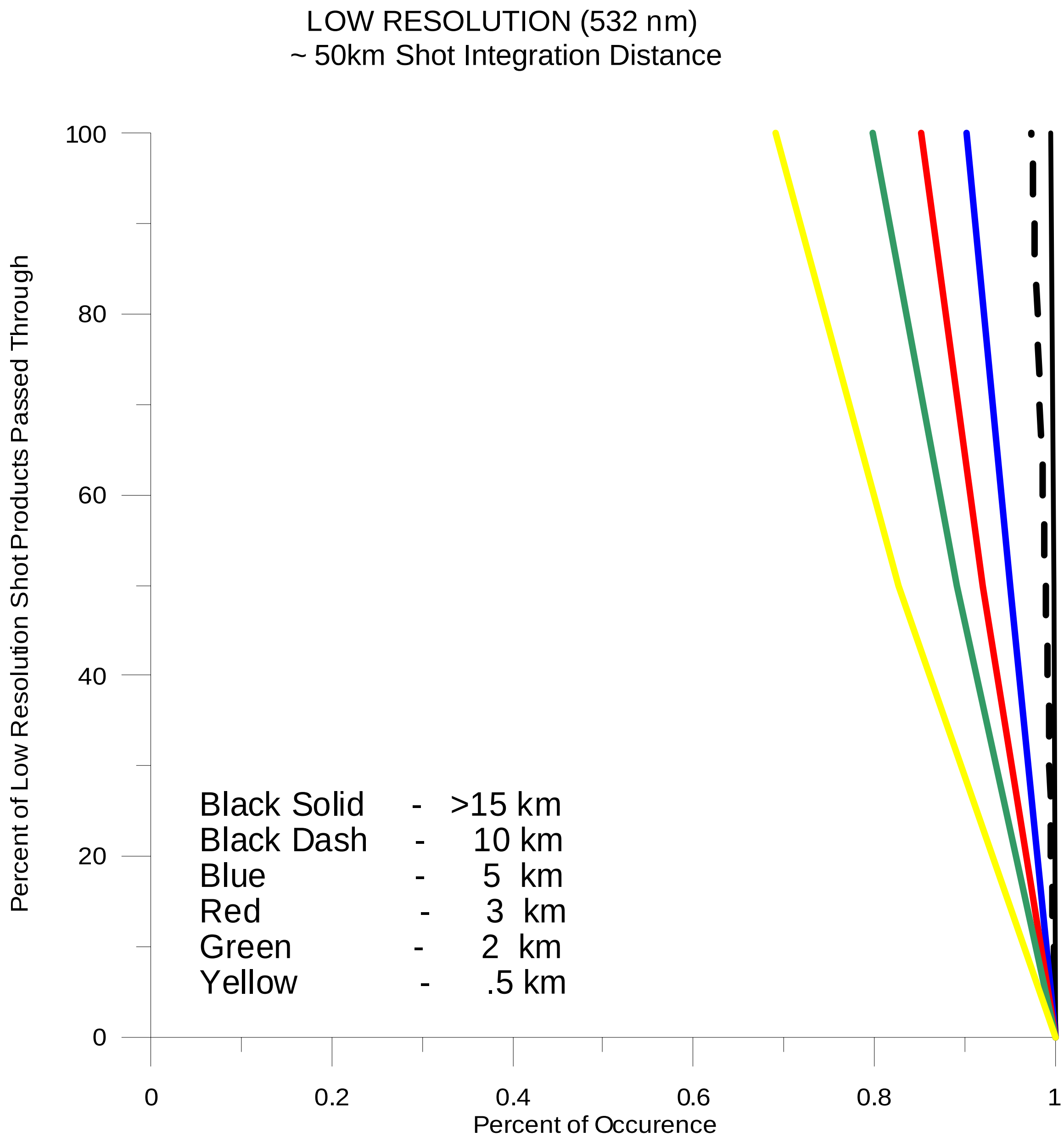

Figure 8: Percent of time various percentages of Low resolution (532 nm) shot products passed through different levels of the atmosphere for an integration length of ~ 50 km.

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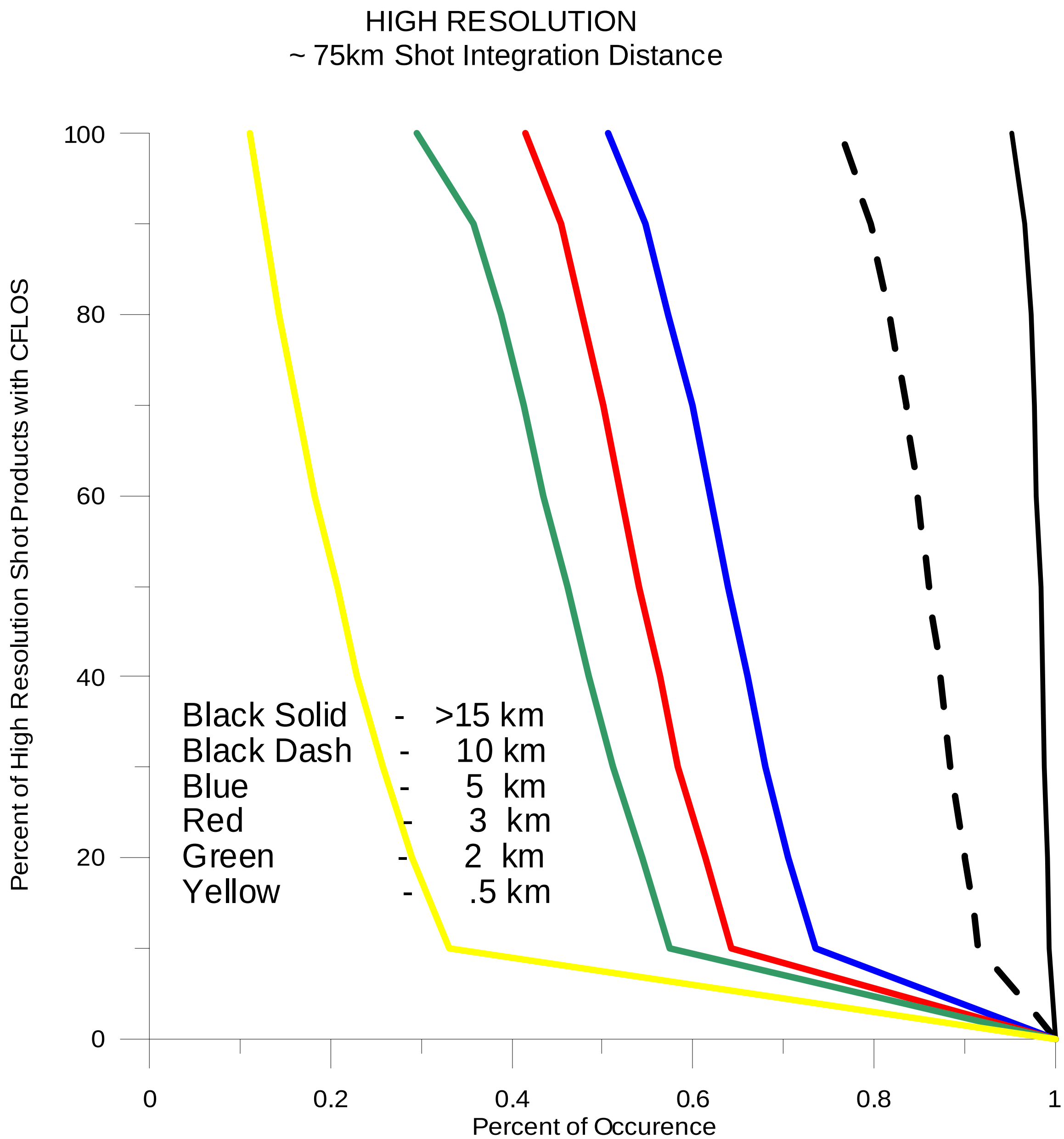

Figure 9: Percent of time various percentages of High resolution shot products had a CFLOS down to a given altitude over a ~ 75 km distance

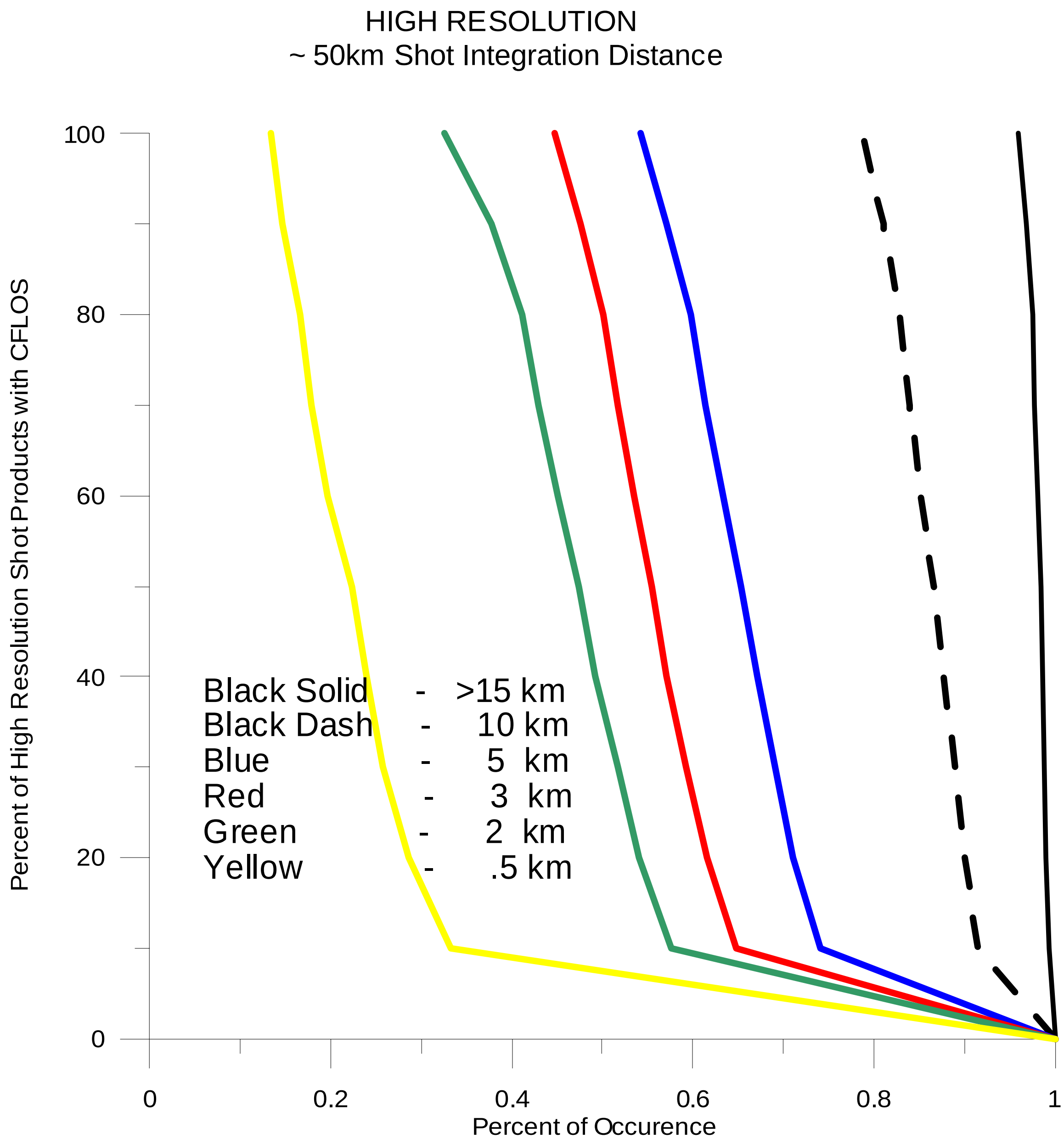

Figure 10: Percent of time various percentages of High resolution shot products had a CFLOS down to a given altitude over a ~ 50 km distance

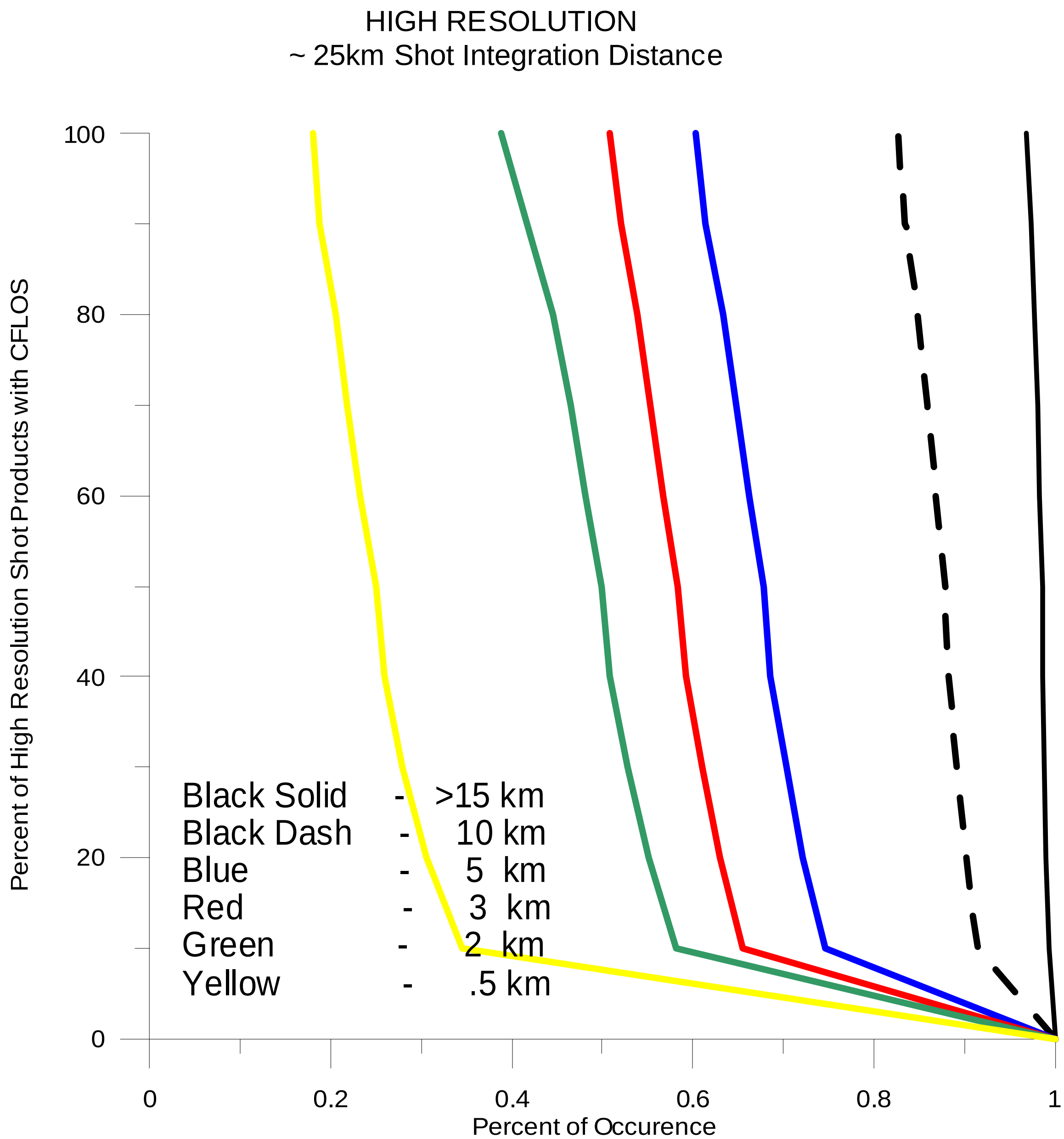

Figure 11: Percent of time various percentages of High resolution shot products had a CFLOS down to a given altitude over a ~ 25 km distance

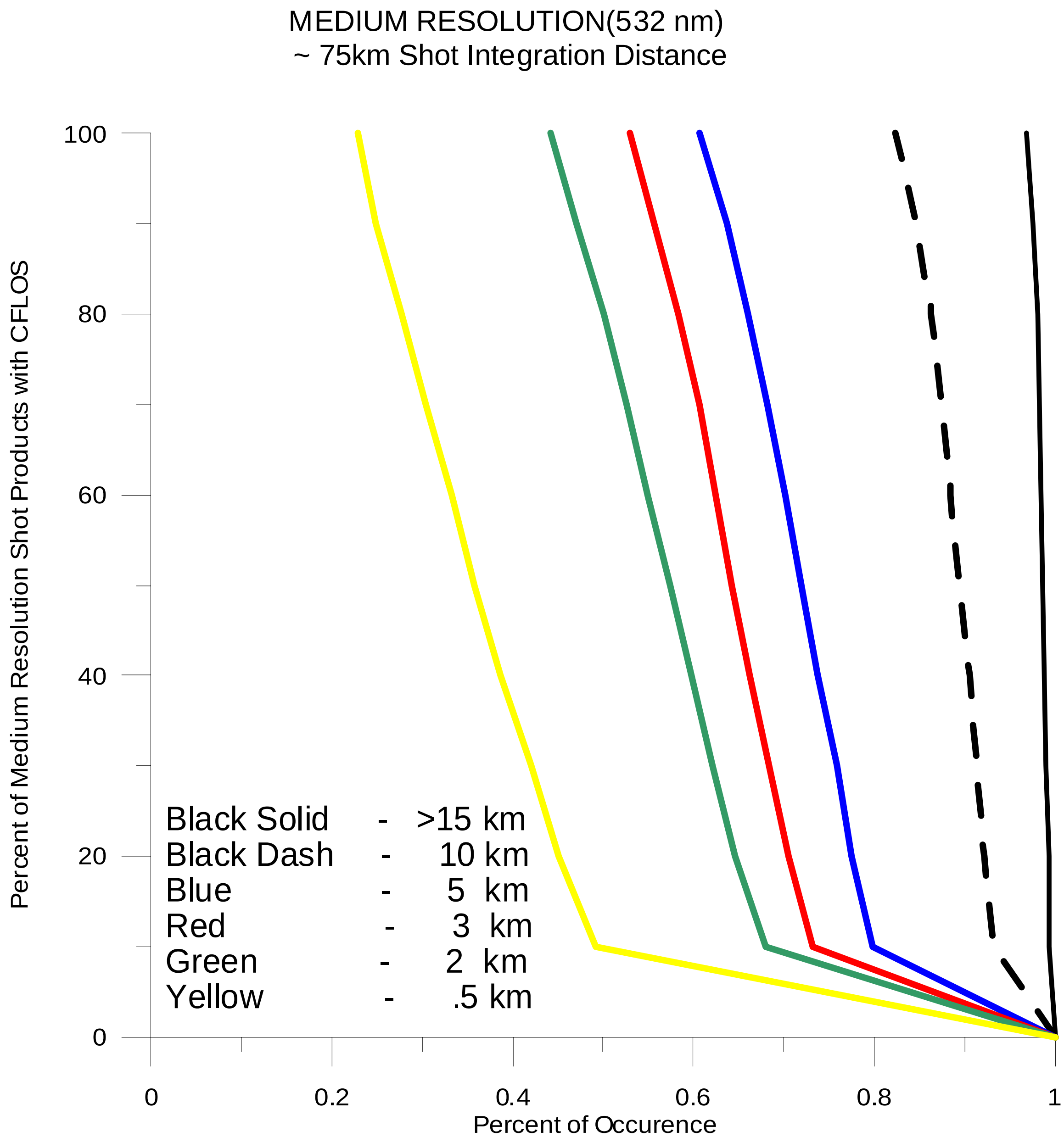

Figure 12: Percent of time various percentages of Medium resolution (532 nm) shot products had a CFLOS down to a given altitude over a ~ 75 km distance

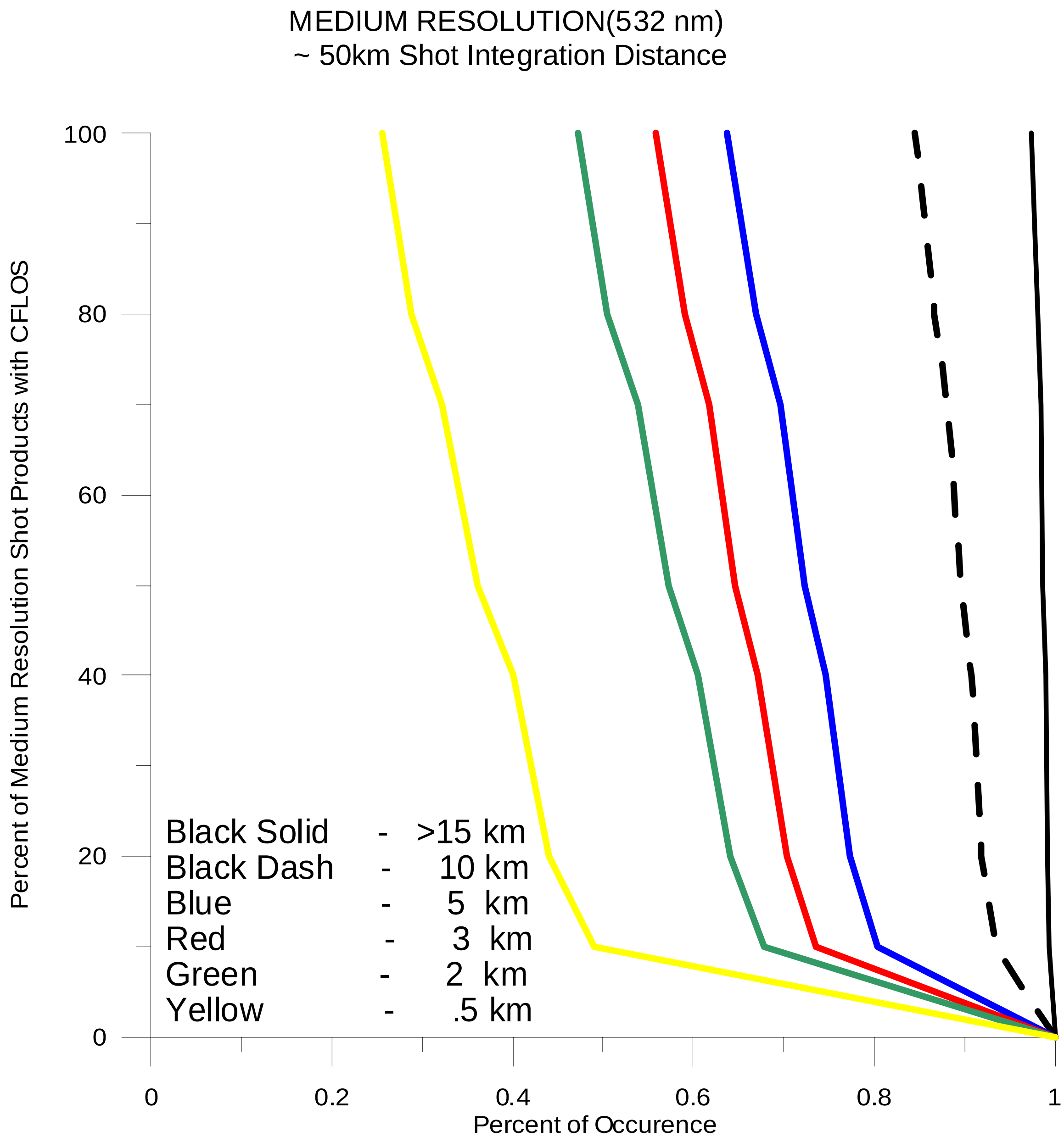

Figure 13: Percent of time various percentages of Medium resolution (532 nm) shot products had a CFLOS down to a given altitude over a ~ 50 km distance

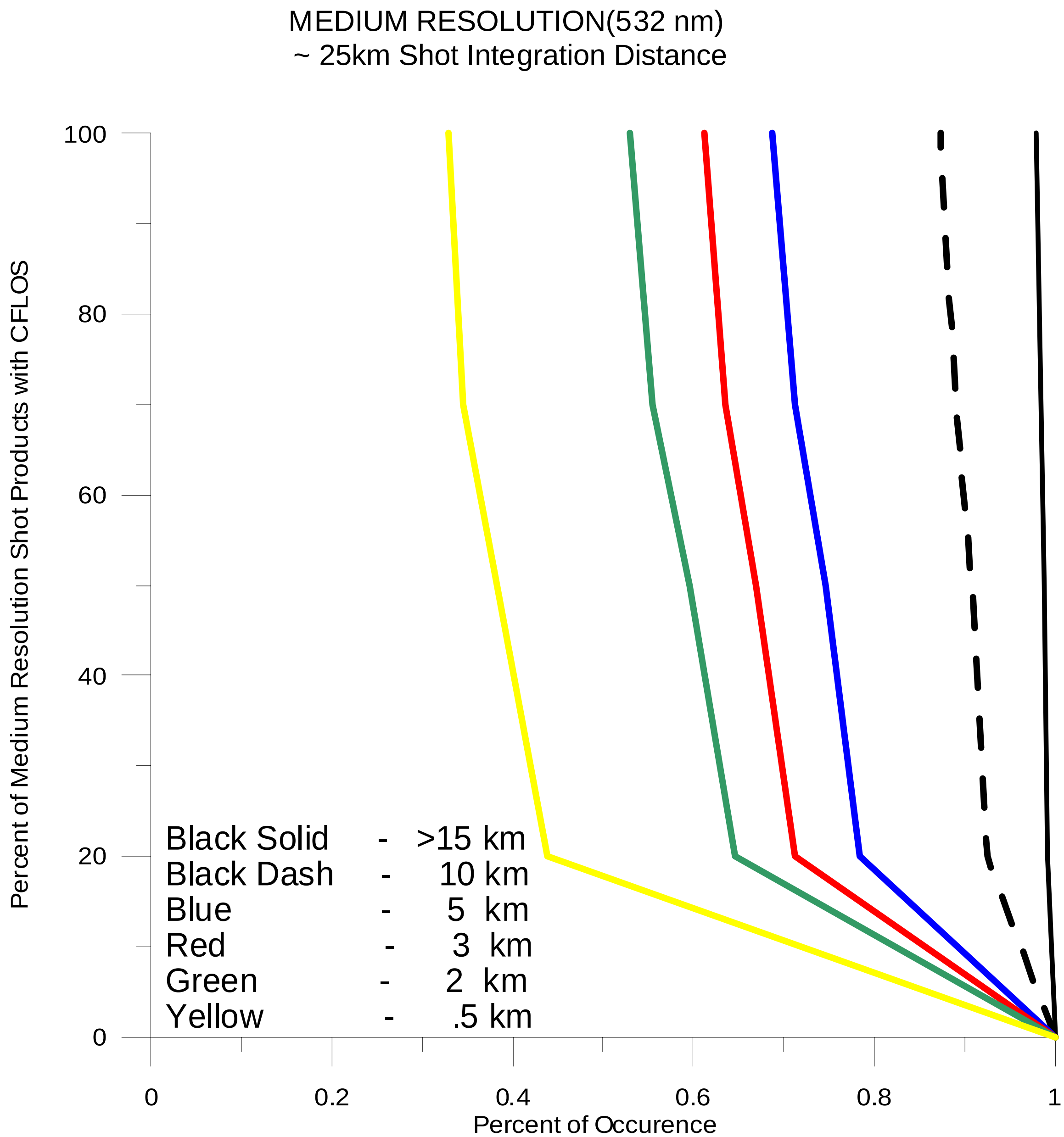

Figure 14: Percent of time various percentages of Medium resolution (532 nm) shot products had a CFLOS down to a given altitude over a ~ 25 km distance

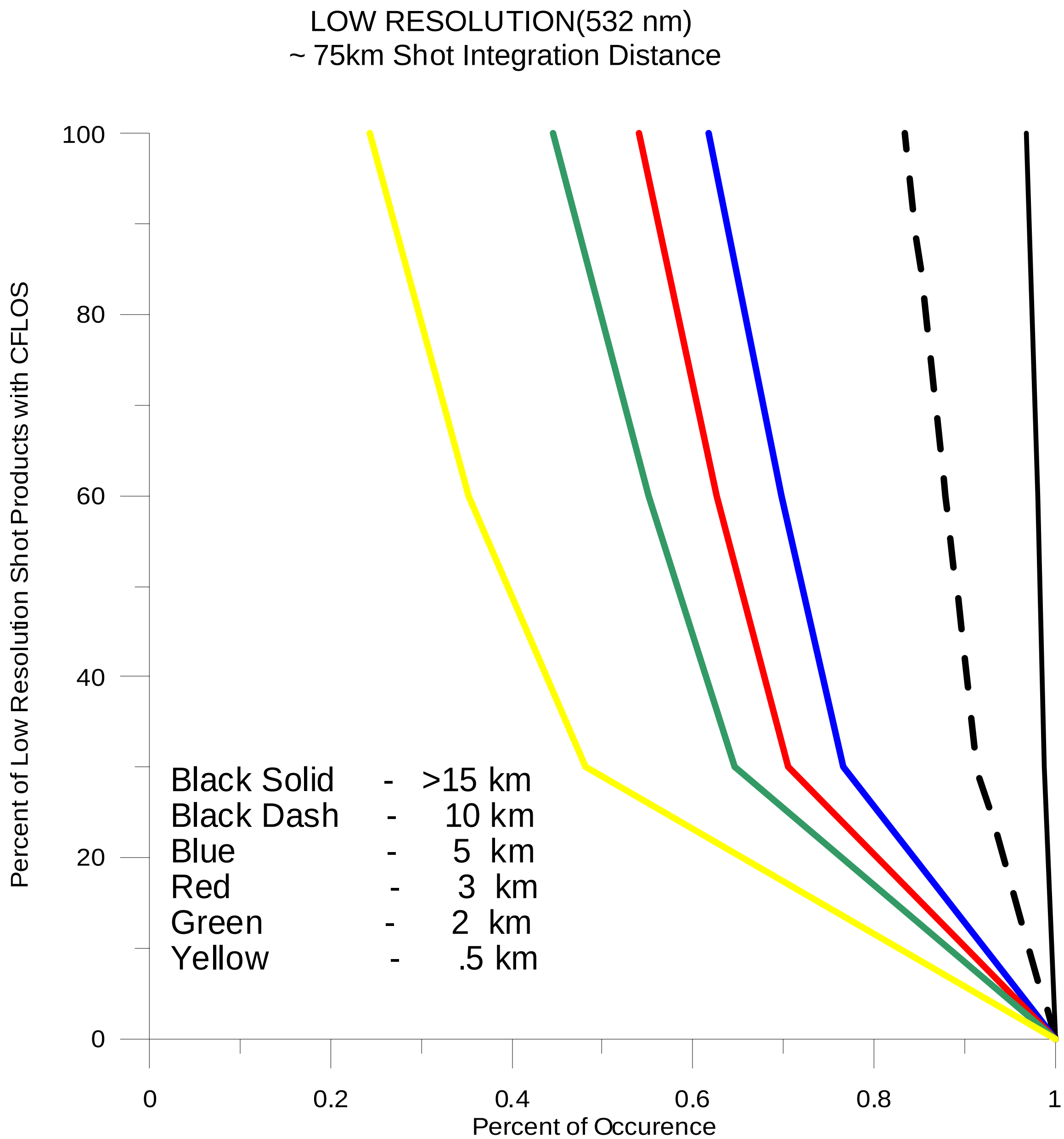

Figure 15: Percent of time various percentages of Low resolution (532 nm) shot products had a CFLOS down to a given altitude over a ~ 75 km distance

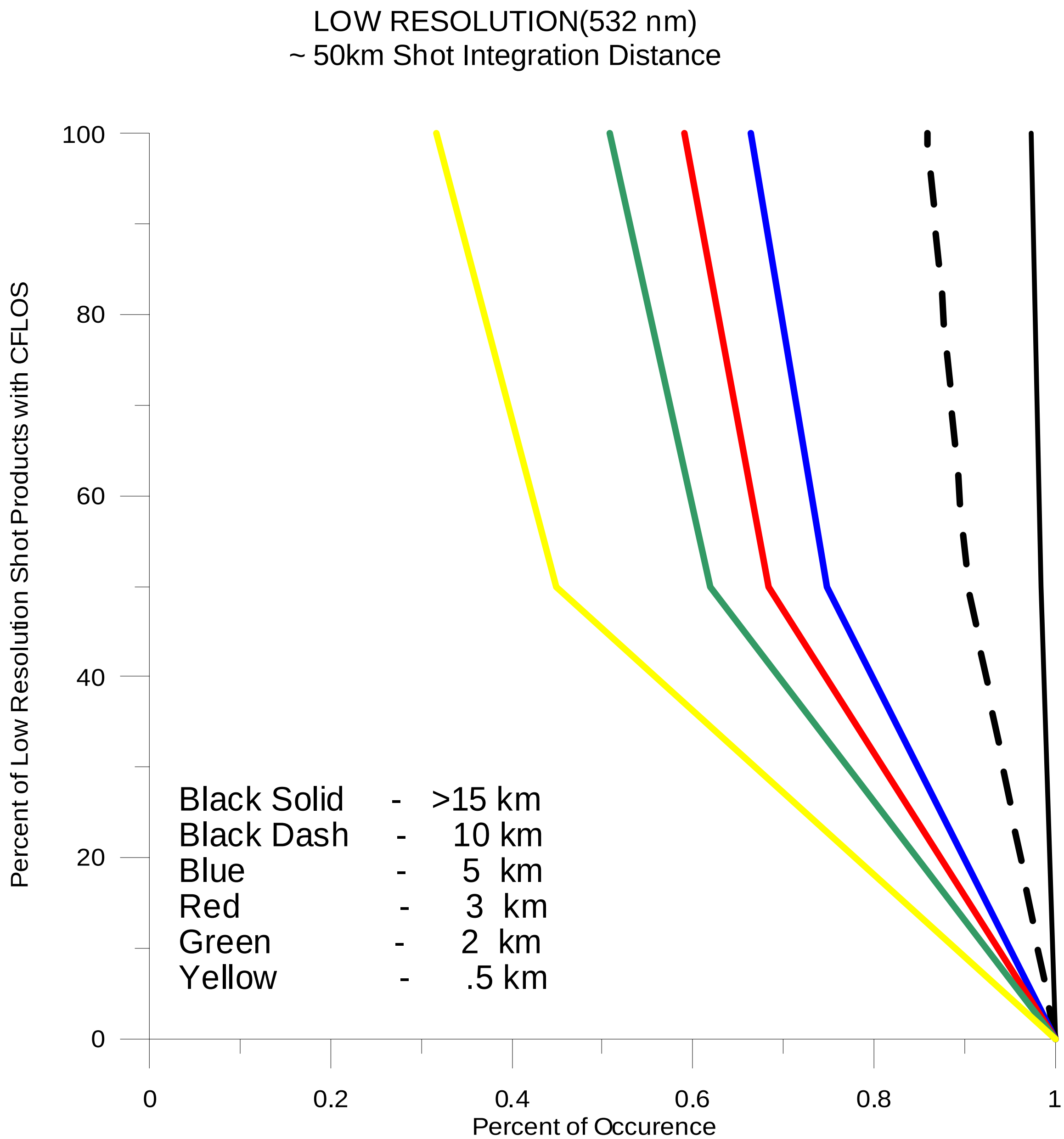

Figure 16: Percent of time various percentages of Low resolution (532 nm) shot products had a CFLOS down to a given altitude over a ~ 50 km distance

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