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14. ABSTRACT
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Optimal GEO lasercomm terminal field of view for LEO link support

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ABSTRACT

As alternatives to the traditional gimbaled terminal design, future satellite based laser communications terminals are envisioned that utilize a wide field of view or field of regard (WFOV/WFOR). This approach can be advantageous in situations requiring rapid switching between user terminals, support for multiple terminals simultaneously (via TDMA, SDMA or WDMA) or other non-standard mission requirements. However, a traditional gimbaled terminal has the capability to continuously track a single user over very large angles, such as the 18-20° spanned by a LEO satellite as seen from GEO. WFOV/WFOR designs face increasing cost and/or complexity issues with each incremental increase in angular coverage. The methodology and inputs for a trade study are presented here that attempts to maximize the available connectivity to a LEO satellite while minimizing cost and complexity metrics by choosing an optimal FOV/FOR size for a GEO terminal.

Keywords: Lasercom, field of view, satellite availability, wide field optical design

1. Introduction

Laser communications systems for space to space applications are increasingly attractive to systems designers in recent years due to their high bandwith, low Size, Weight and Power (SWaP), secure nature, advances in component technologies, and the lack of atmospheric distortions or losses in space. The same benefits also accrue for links between spacecraft and aircraft that are flying high enough to be above most of the atmospheric distortions. Several existing or planned systems have been designed to take advantage of the benefits of laser communications technology (and like any new technology, there have been several false starts as well) [1-5].

The conventional design approach for a space-based laser communications system is to use a gimbal or some other mechanical-type coarse steering mechanism to steer the FOV and track the desired user [6-8]; laser communications terminals are usually support payloads and slewing the whole spacecraft to achieve the desired pointing is not a viable solution. In such a system, the FOV will typically be quite small (~10 mrad or smaller) for background light rejection and ease of optical design. Switching from one satellite to the next will therefore require slewing the gimbal to the new position (unless the target satellites are very tightly spaced). Additionally, such architectures are limited to only supporting 1 user at a time, unless other users are very closely spaced.

An alternative approach to achieve greater functionality would be to employ an optical system with a wider field of view to enable seamless switching between users and/or support for multiple simultaneous users. Ideally the system would have a large enough field of view to encompass all potential users simultaneously, but due to the optical design complexity and SWaP issues this may not be possible; therefore one is left to trade a wider field of view against some measure of increased utility.

The remainder of this paper explored these issues in more detail. Section one details a trade study to look at how increasing the field of view impacts the design of an optical system, and develops a relationship between FOV and

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telescope volume. Section two describes how increasing the field of view affects the overall availability/utility to communicate with a LEO satellite terminal from a GEO platform. Section three then combines these two results and performs the trade to determine the optimal field of view.

2. OPTICAL DESIGN

A crude scaling was performed to determine the associated system cost for increasing the full field of view of an optical system by examining a representative design for each field of view range [9]. A total of five systems were examined in ZEMAX, each with a 100mm entrance pupil, corresponding to systems having at most 1, 6, 20, 40 and 100 degrees full field of view, with the volume consumed by the optics (and NOT including any necessary housing or support structures) calculated in each case. Each system was intended to be representative of what would be required to achieve the desired field of view, but the designs are not by any means actual flight designs and are intended as a rough gauge only.

The first system considered for the 1° FOV case is a standard Ritchey-Chretien Cassegrain design, shown in Figure 1. This design is relatively compact, with a total length of 16.3cm, and the computed volume comes to 67.8 cm^2.

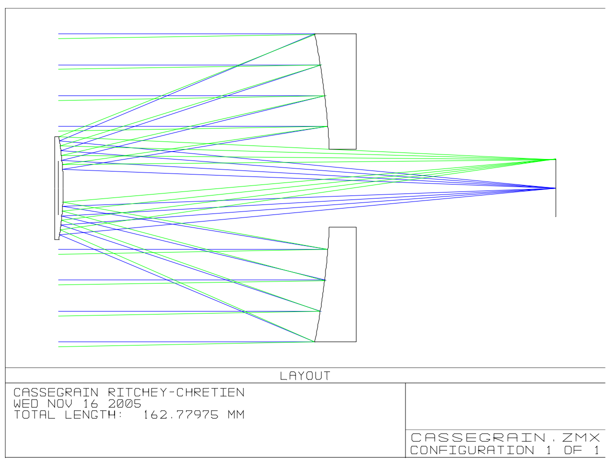

Figure 1: 1 Degree FOV Design

Moving to a slightly wider field of view system such as a 6° design requires going to a Schmidt-Cassegrain approach with the addition of a refractive corrector plate in front, and produces the longer system shown in Figure 2. This system is nearly 5 times longer, at 78 cm, and takes up a volume of 333 cm^3.

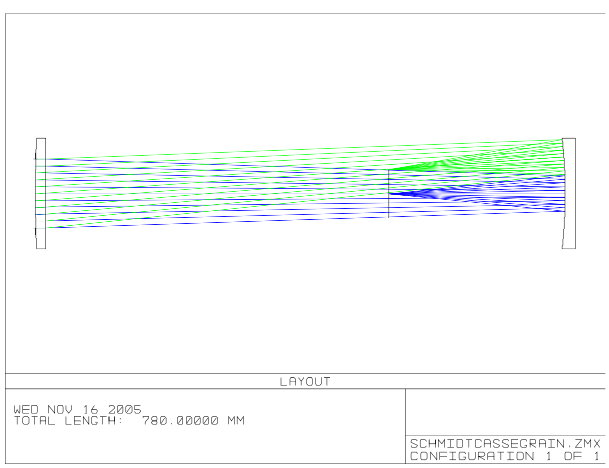

Figure 2: 6 Degree FOV Design

Surprisingly enough, going to the next larger FOV limit (20°), produces a design that is slightly shorter (at 61 cm) than the 6° design. In this case, a simple Cooke triplet is employed to get to the desired FOV, as shown in Figure 3 below, and this design comes in at a volume of 804 cm^3.

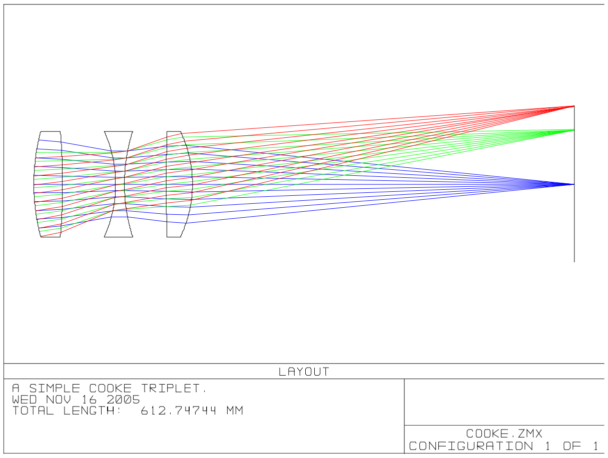

Figure 3: 20 Degree FOV Design

The designs begin to become much more complicated as the FOV is increased even farther. The 40° design seen in Figure 4, employs a total of 6 optical elements in a double Gaussian configuration and, although it is only 66 cm long, consumes a prodigious 7750 cm^3 of volume.

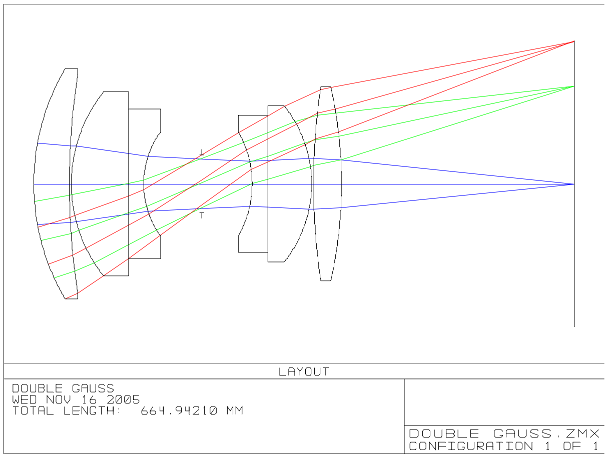

Figure 4: 40 Degree FOV Design

The final design considered is a 100° Laikin-type wide angle lens as shown in Figure 5. This design employs 12 optical elements, is over 219 cm long, and takes up a rather hefty 188,549 cm^3 of volume!

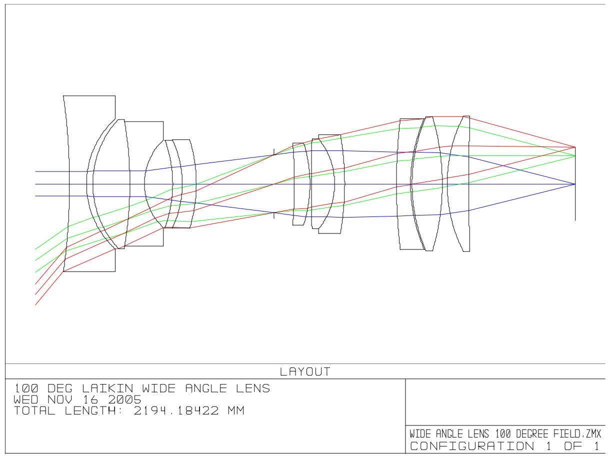

Figure 5: 100 Degree FOV design

All 5 optical designs are shown together on the right side of Figure 6 with the same scale for comparison purposes, and the volumes are plotted as a function of FOV of the left. Note the log scale on the vertical axis for volume; there is over 3 orders of magnitude difference between the 1° and 100° volumes.

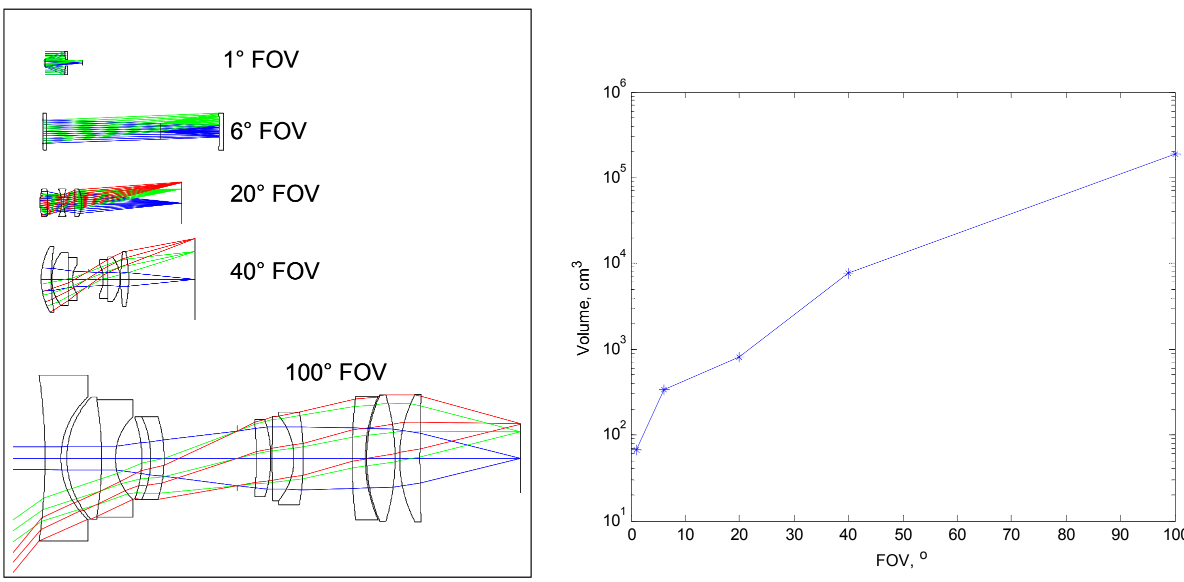

Figure 6: FOV Designs and Volumes

A simple cubic equation was found to adequately represent the relationship between FOV (*F*) and volume (*Vol*), of the form:

$$Vol = -13.01 + 93.55F - 7.760F^2 + .2568F^3 \tag{1}$$

It is recognized that this is a crude approximate at best, but it proved useful as a general scaling law for use in the trade study.

3. SATELLITE CONNECTIVITY VS FOV

A precise study of the connectivity possibilities between a fixed FOV and from GEO to a LEO satellite requires knowledge of the probable fixed locations as well as the LEO satellite ephemeredes or constellation characteristics. In the absence of such information, several assumptions have been made. First of all, the FOV is assumed to be centered at a random location on the earth. The GEO satellite is fixed at the ephemeris data shown in Table 1, while the LEO satellite is assumed to be in a circular orbit at the ephemeris data also shown in Table 1.

Parameter	*Value (GEO)*	*Value (LEO)*
Inclination (i)	0°	0° to 90°
Semi-major axis (a)	42,164 km	6628-7378 km
Longitude of ascending node (Ω)	0°	0°
Eccentricity (e)	0	0
Argument of perigee (ω)	0	0
Mean anomaly (M)	0	0

Table 1: GEO and LEO Satellite Parameters

The connectivity over 1 day of operation is used as the baseline for the study, and no attempt was made to adjust the relative starting positions as several ground tracks are visible during this period, as shown in Figure 7, which shows the ground track for 1 day for a 90° inclination LEO at 1000 km altitude. A simple orbital propagator was developed in MATLAB from [ref], and no higher-order terms or perturbations were applied. Portions of the ground track obscured by the Earth were removed from consideration.

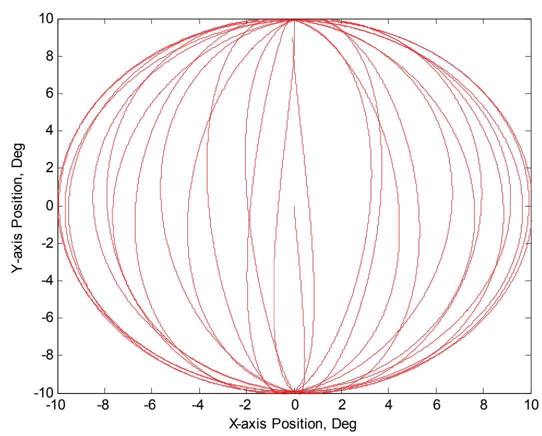

Figure 7: LEO Satellite Ground Track

A simulation was developed to place 1000 randomly located FOVs on the earth and calculate the connectivity within each FOV. This was done by determining which portions of the ground track were contained within each FOV, and determining the duration for each segment contained therein. A sample of 100 such FOVs for the 1° case is shown in Figure 8; note that many of the locations at this small FOV do not contain any ground tracks, and would be useless for this particular LEO during this particular day.

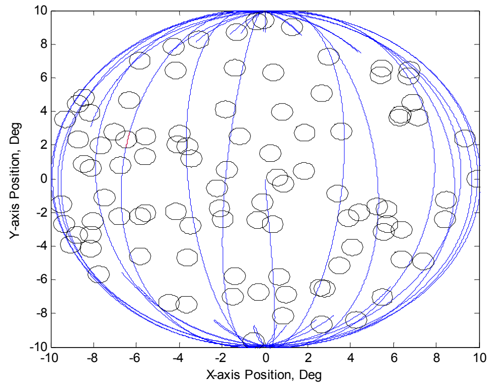

Figure 8: 1 Degree FOV Locations

Based on the 1000 samples collected for each FOV, statistics are generated to determine the degree of connectivity offered. In the case of the 1° FOV, the probability of achieving n hits during a 24 hour period is shown in Table 2, while the CDF for connectivity duration (given that there is a hit) is shown in Figure 9. Finally, a histogram for duration is shown in Figure 10.

# of Hits	*Probability*
0	56.5%
1	41%
2	2.3%
3	.1%
4	.1%

Table 2: # Hits vs Probability, 1 Degree FOV

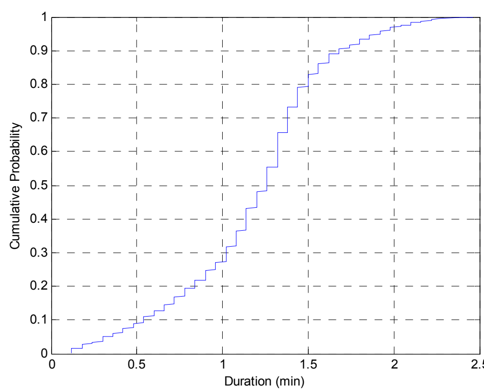

Figure 9: Cumulative Probability Distribution Function, 1 Degree FOV

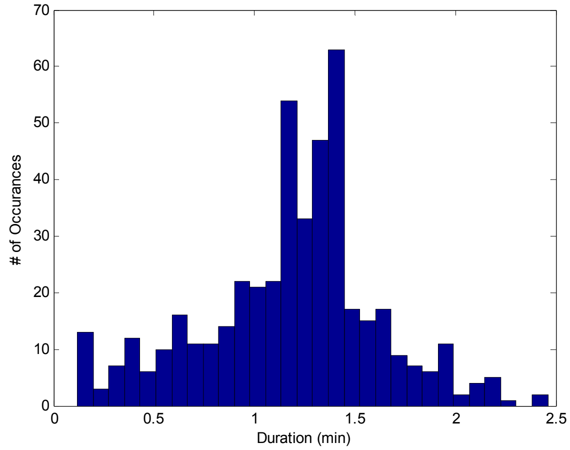

Figure 10: Duration Histogram, 1 Degree FOV

This same procedure is then repeated for FOVs of 2, 3, 5, 10 and 20 degrees; for the 20° case the starting location was assumed to be a constant at the center of the earth as the FOV is in this case large enough to encompass the entire earth and the LEO tracks.

The first result shown from this simulation appears in Table 3. This table attempts to demonstrate the likelihood of having the LEO satellite with the GEO terminal's FOV during 1 day of operations. The result follow the intuitive understanding that the larger the FOV, the more likely you are to see the LEO satellite.

	FOV					
# of Hits	**1°**	**2°**	**3°**	**5°**	**10°**	**20°**
0	56.5%	23.1%	8%	0.2%	0.0%	0.0%
1	41%	60.0%	46.5%	3.7%	0.0%	0.0%
2	2.3%	11.6%	30.9%	28.6%	0.2%	0.0%
3	.1%	3.3%	2.7%	20.0%	11.8%	0.0%
4+	.1%	1.9%	12.0%	47.2%	88.0%	100.0%

Table 3: Probability of Hit vs FOV

Besides influencing the probability of a hit, the size of the FOV also determines how long a crossing trajectory is visible to the GEO terminal. These results are summarized in Table 4, which gives a minimum connectivity time vs probability and FOV. For example, in the 1° FOV case, 10% of the time a satellite passing through the GEO terminal's FOV will be visible for less than 40 seconds; 50% of the time it will be visible for less than 79 seconds, and 90% of the time it will be visible for less than 112 seconds. Note that these probabilities do no take into account instances where the satellite is not visible at all.

	View time (sec) vs FOV					
Conf. Level	**1°**	**2°**	**3°**	**5°**	**10°**	**20°**
10%	40	72	112	162	238	432
25%	65	119	187	306	544	479
50%	79	166	252	425	864	932
75%	94	191	292	497	1022	2318
90%	112	238	346	612	1952	2520

Table 4: Minimum Connectivity Time vs FOV

An alternative approach is shown in Figure 11, which shows the cumulative distribution functions for each FOV (20° is not shown as due to its special nature as the limiting case; it is shown separately in Figure 12).

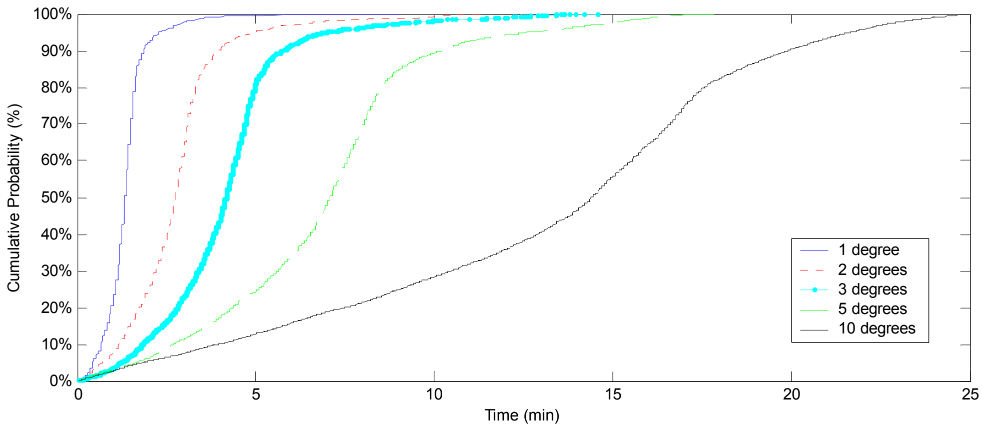

Figure 11: Cumulative Probability Distributions

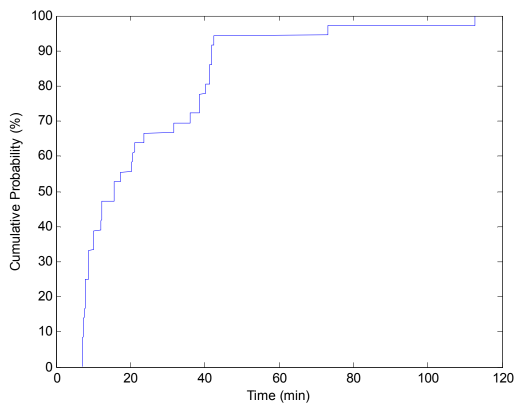

Figure 12: CPDF for 20 Degree FOV

4. FOV TRADE STUDY

Now that results for both FOV vs volume and FOV vs connectivity time are available, we can combine the results to show connectivity vs volume. If we take a constant cumulative probability level from Figure 11 (say at the 90% level), we get a curve of time vs FOV; this is shown in Figure 13 (left) for the 90% case. In this case, a scaling of the form:

$$T = 2F - .1 \tag{2}$$

Where (T) represents time in minutes and (F) is field of view in degrees matches the data quite closely. Given equations (1) and (2), an equation relating volume to availability time can be found:

$$Vol = -13.01 + 93.55\frac{T+.1}{2} - 7.760\left(\frac{T+.1}{2}\right)^2 + .2568\left(\frac{T+.1}{2}\right)^3 \tag{3}$$

Equation (3) is shown in on the right half of Figure 13.

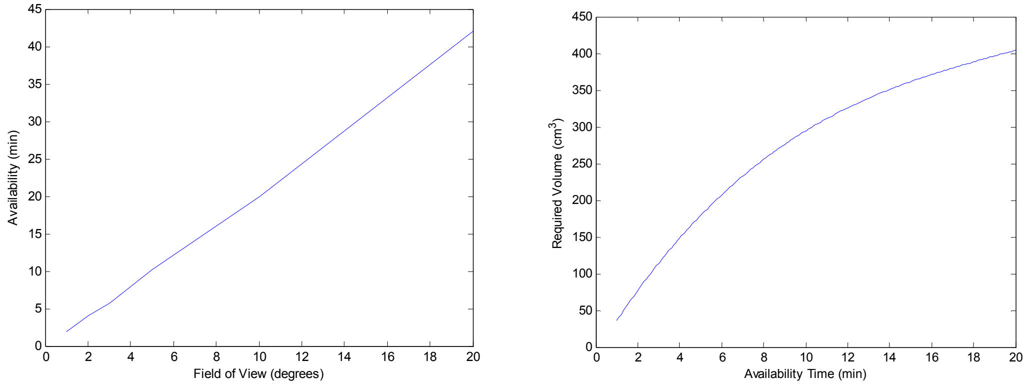

Figure 13: Availability vs FOV (left), Volume vs Time (right)

An alternate approach is to take the total availability time for each FOV and subtract off any engagements that last less than some threshold set by the system acquisition requirements. If we assume an acquisition is budgeted for 45 seconds, the resulting curve is shown in Figure 14 (note the log scale on the availability time axis). By following the same procedure outlined above, a relationship between availability and volume was found and is shown in Figure 15. Surprisingly, the total availability defined in this manner increases exponentially with respect to the required volume.

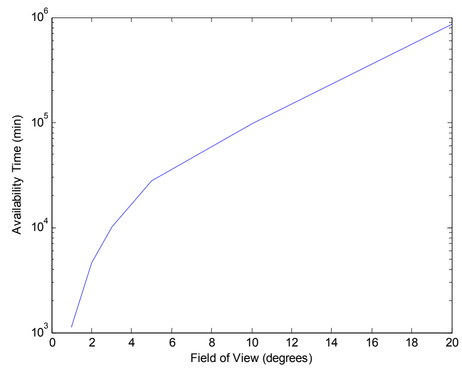

Figure 14: Total Availabity minus Acquisition Time

A full trade study to then optimize the FOV can now be preformed given access to the rest of the system design parameters such as available SWaP, required daily communications throughput, connectivity time lost to acquisition, cost of additional narrow FOV gimbaled terminals and other relevant system parameters. It is clear from Figure 15 that availability grows exponentially with respect to optical volume (and hence SWaP), so the designer interested in this type of architecture is going to be driven to the largest FOV system that fits within the system constraints that are provided.

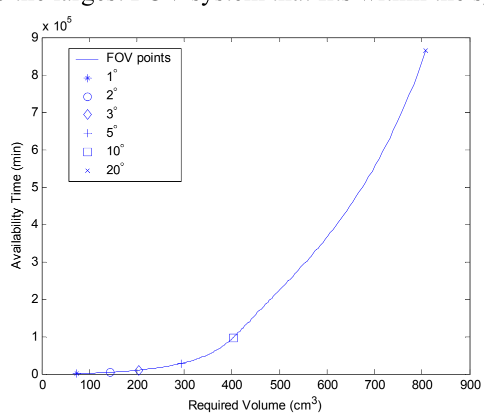

Figure 15: Volume vs Total Availability

5. CONCLUSIONS

A survey of optical designs was conducted and a rough gauge of optical system volume vs FOV was constructed. It was found that optical system volume increases at a cubic rate over the range considered. Next a study was performed to determine the view availability between a GEO terminal and a LEO satellite in a polar orbit over 1 day with varying FOV sizes and fixed locations. A series of availability time probability curves were constructed from this study, and this data was combined with the optical system data to determine the relationship between optical system volume and availability time. It was found that the availability time increases at an exponential rate compared to the volume.

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