The Impact and Resolution of "Collision Bands" on Tracking Targets at Various Ranges

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Abstract

Symmetric SLR and LLR systems that adopt a spinning disk as an optical switch between transmit and receive laser pulses need to address the problem of losing signal due to transmit and receive pulses being coincident at the disk when targets are at certain "collision band" ranges. These collision bands occur with increasing frequency at larger target ranges and can interrupt tracking of distant targets (> 6,000 km) for significant periods. A general solution to minimize the impact of collision bands based on disk frequency adjustment is presented. Depending on the design of the disk and system requirements, it is possible to eliminate the effect entirely or reduce the impact to a few narrow range bands by applying a relatively simple disk frequency control algorithm.

Introduction

Satellite Laser Ranging (SLR) stations that employ a symmetric (i.e. single telescope) system for their transmit and receive paths must adopt a multiplexing mechanism to allow measurement of the timing of the transmitted and received laser pulses. One popular mechanism involves the use of spinning mirrored disk containing one (or more) small holes that allow passage of the transmit pulse, while the mirrored surface is orientated such that return photons are reflected towards a receive detector. This mechanism has been adopted in recent years by EOS Space Systems for a number of their laser tracking system, including the Mt Stromlo SLR system.

One disadvantage of this mechanism is termed the "collision band" problem where a tracking signal is lost due to coincidence of a transmit hole and returning photons. The collision band thus refers to the band of target ranges that are effectively unmeasurable due to this coincidence. To increase the transmit power it can be advantageous to increase the number of transmit holes, which for a given disk rotation frequency, allows a greater laser fire rate. Unfortunately the greater the number of transmit holes, the greater the number of collision bands that may be experienced with potential loss of signal.

One technique used to minimize of collision bands relies on adjustment of the disk frequency and thus laser fire rate. For example, Titterton (1998) describes this technique to minimize backscatter. This paper describes an analysis of this collision band problem and proposes a technique for the automatic minimization of collision bands and number of disk frequency adjustments for a given range of disk configurations.

Theory

Collision Band Model

Spinning transmit/receive (T/R) disks often have one or two transmit holes, but in general there could be any number subject only to physical restrictions. Figure 1 shows a schematic of such a disk having two transmit holes. In general we can let; **N** = number of holes equally spaced around the disk, **r** = radius of the transmit hole, **R** = radius of 'projected' circle containing the transmit hole centre at fire time, and **f** = disk speed (Hz), giving the laser fire rate as **Nf**. Also let **α** = angle subtended by each transmit hole such that $\alpha = 2\sin^{-1}(\mathbf{r}/\mathbf{R})$.

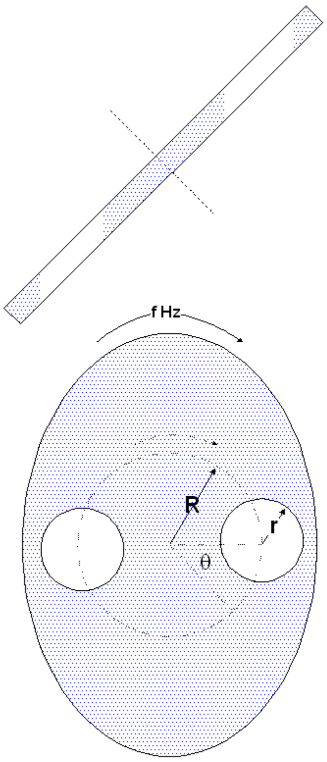

Figure 1: *Schematic of theSpinning T/R Disk*

s = available signal as a ratio, i.e. **s** = 1 when there is no loss and outgoing and incoming signals do not overlap, or **s** = 0 when complete overlap occurs.
d = distance of the target (along the optical path), and **c** = speed of light, such that the two-way time taken for a reflected pulse to leave and return to the disk is **τ = 2d/c**.
Let **θ** = angular displacement on the 'projected' circle. Given the rotation speed of a point on this circle is **2πf**, then the disk rotational movement, **Δθ,** in the time it takes for a laser pulse to leave and to return, **Δθ** = **2πfτ,** is limited to

$$\frac{2\pi\, i}{N} - s\alpha < \Delta\theta < \frac{2\pi\, i}{N} + s\alpha$$

Here **i** is an integer, equivalent to the number of shots in flight.

Assume that **α** = 2**r**/**R** to a good approximation and define a geometrical factor, **F** = **sr/R**. This equation can be then be rewritten to give the condition for the existence of a collision band, i.e.,

$$\frac{i}{N} - \frac{F}{\pi} < f\tau < \frac{i}{N} + \frac{F}{\pi}$$

which can be expressed simply as,

$$\left| f\tau - \frac{i}{N} \right| < \frac{F}{\pi} \qquad (1)$$

The number of pulses in flight, **i**, can be determined from $i = [N\tau f]$, but it is wise to confirm the inequality using "floor" and "ceiling"values; i.e. $i = \lfloor N\tau f \rfloor$ and $i = \lceil Nf\tau \rceil$.

Frequency Shifting

Equation (1) indicates that for a given range, **d**, and a given geometrical configuration there is only one parameter that can be adjusted such that the inequality no longer holds and that is the disk frequency, **f**. Hence it may be possible to adopt a scheme where the effect of collision bands can be reduced, or even eliminated, by frequency shifting the spinning disk.

From equation (1) it can be shown that to avoid a collision band at a given range, **d** (or equivalently, **τ**) then set **f** such that

$$\left| Nf\tau - [Nf\tau] \right| \geq \frac{NF}{\pi} \qquad (2)$$

There may be additional system restrictions on the spinning disk frequency, the range of frequency adjustments that can be made and on the rate that adjustments can be made. The restrictions may be such that condition set by equation (2) cannot be met and the collision band cannot be avoided.

The next section describes an analysis of a typical two hole disk used in a laser tracking system and the scheme used to meet, as much as possible, the collision band avoidance condition given by equation (2).

Analysis of a Two Hole T/R Disk

Consider a two-hole disk having a geometrical factor F of 20%. For example, a disk where the transmit holes have a radius (projected at right angles to the laser beam) of 15 mm, at a radius from disk centre of 75 mm, or a disk with transmit holes of radius 12 mm at a distance of 60 mm from the disk centre will have F = 20% assuming no overlap of the return beam footprint on the transmit holes (s = 1.0). For this analysis assume that the maximum laser fire rate is 100Hz and the maximum frequency variation is ±5%. This is just one example of possible design constraints that might apply to systems using this technique. In this case, the value of **f** is limited to a range between 45 and 50 Hz

***Table1:** Defined Range Bands*

Range Band	Sample Ranges (km)
Low Earth Orbit (LEO)	500 – 2000 km
Medium Earth Orbit (MEO)	2000 – 12000 km
High Earth Orbit (HEO)	19000 – 29000 km
Lunar	350000 – 400000 km

Table 1 summarises the four range intervals used in this analysis. These represent the typical distribution of earth orbit satellite and lunar targets. Equation (1) was applied to range values in each of these intervals to identify the collision bands occurring over the various ranges. The following sections describe the results from these calculations. In all cases the disk frequency resolution used was 0.05 Hz.

Impact of Tracking LEO Satellites

No collision bands are evident for low earth orbit ranges less than about 1,300 km as shown in figure 2. Unfortunately a collision band occurs for ranges from approximately 1450 km to 1700 km which cannot be avoided using the available disk frequency shift.

An assessment has to be made whether this collision band will cause significant impact on actual target tracking.

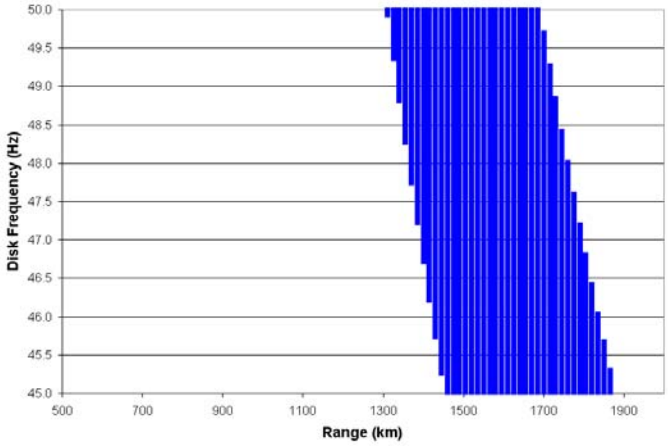

***Figure 2**: Collision Bands at LEO Satellite Ranges*

Impact on Tracking MEO Satellites

For ranges between 2,000 and 12,000 km, the collision bands are grouped as shown in figure 3. There are also significant range intervals where there are no collision bands at all. However there is still one range interval where there is an unavoidable collision band, at about 3,000 to 3,200 km. Above this interval there are no ranges that have an unavoidable collision band, as illustrated in figures 3, 4 and 5.

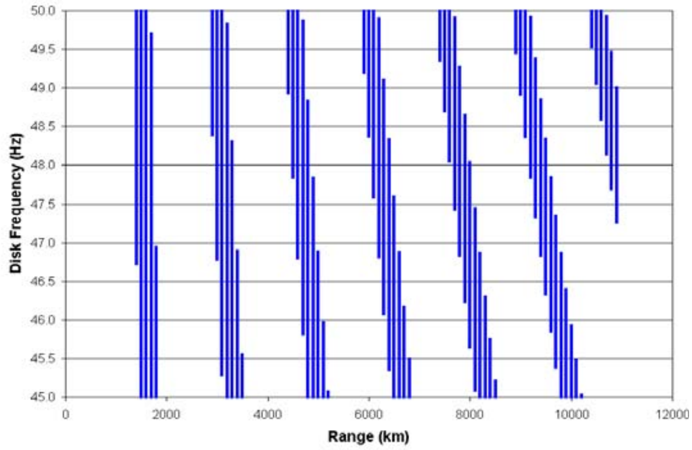

***Figure 3**: Collision Bands at MEO Satellite Ranges*

Impact on Tracking HEO Satellites

As ranges increase, the number of collision bands within the disk frequency range increase and become shorter, as illustrated in figures 4 and 5, so the options for avoiding collision bands also increases. However, for any given disk frequency, the probability of a target pass having a number of collision bands also increases.

It is notable that even for one-hole disk systems, the probability that a high satellite pass contains one or more collision bands is quite high, and hence an avoidance scheme is still required.

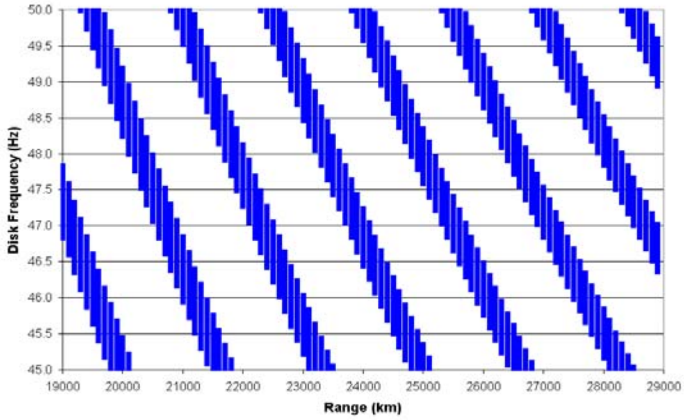

***Figure 4**: Collision Bands at HEO Satellite Ranges*

Impact on Tracking Lunar Targets

At lunar target distances, collision bands are very frequent but very short both in terms of disk frequency and range changes as illustrated in figure 5. With slowly changing ranges, it is possible that a lunar target pass may either be largely free of collision bands or be largely in a collision band. Avoidance at these ranges will require small shifts in disk frequency. Table 2 shows a summary of typical impact of collision bands on tracking a number of ILRS SLR satellites and LLR targets.

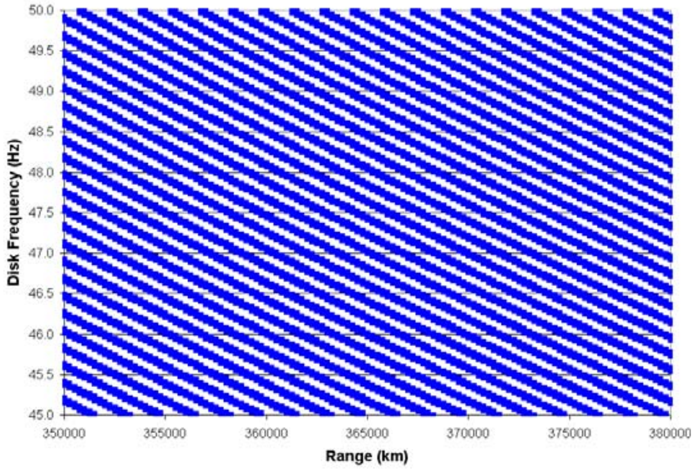

***Figure 5**: Collision Bands at Lunar Ranges*

***Table 2**: Impact of Collision Bands on ILRS Satellites*

Satellite Groups	Typical Ranges (km)	Impact, no avoidance	Impact with avoidance
GraceA & B, Champ	500 – 1500	None	None
Envisat, ERS2, GFO1, Stella, Starlette	800 – 2000	Lost data around 1500-1700 km (near end of passes)	Lost data around 1500-1700 km (near end of passes).
Ajisai, Jason	1400 – 2900	Lost data near zenith of high passes.	Lost data near zenith of high passes.
Lageos1,2	5900 – 9,000	Lost data in 1 or 2 bands.	None
GPS, Etalon, Giove A, Galileo	19,000 – 27,000	Lost data in 2 or 3 bands.	None
LLR targets	350000 – 420,000	Significant periods of lost data	None

Collision Band Avoidance

Frequency Shifting Algorithm

Using equation (1) it is straightforward to assess, given current range and disk frequency, whether a tracking system is experiencing a collision band. However it is less straightforward to determine what is the best disk frequency to use to avoid such a band. An algorithm was devised such that not only are collision bands avoided (if at all possible) but the number of

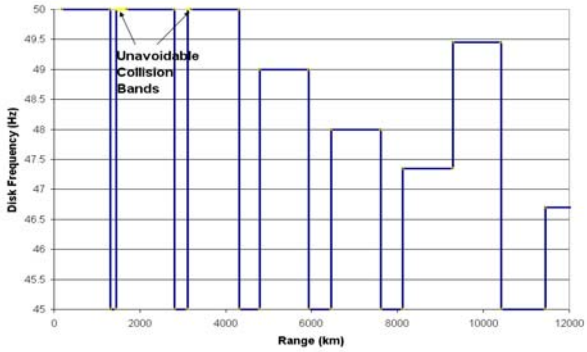

Figure 6: *Disk Frequency over increasing LEO and MEO Satellite Ranges*

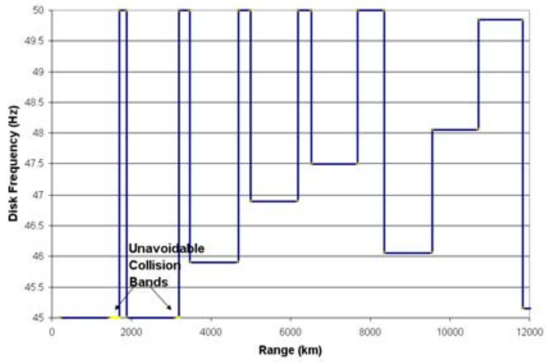

Figure 7: *Disk Frequency over decreasing LEO and MEO Satellite Ranges*

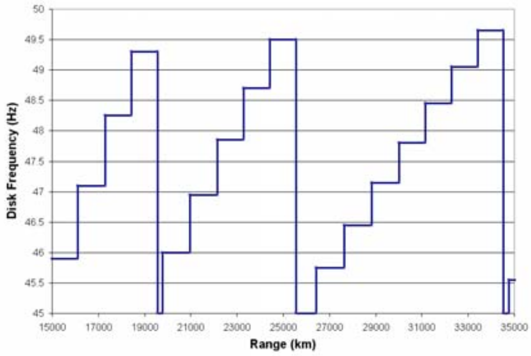

Figure 8: *Disk Frequency over increasing HEO Satellite Ranges*

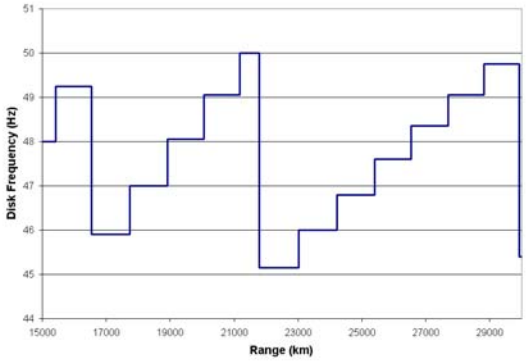

Figure 9: *Disk Frequency over decreasing HEO Satellite Ranges*

frequency adjustments is minimized. This may be important if the time taken for the laser system to respond to frequency changes is significant.

The algorithm requires determining, for a given range, the disk frequency end points of a given collision band, at the moment that this collision band is first encountered. No action (i.e. frequency adjustment) is necessary when a collision band is not present. If a collision band is encountered when the range is increasing, increase the disk frequency by a small amount and check if the collision band is still present. This is repeated until maximum disk frequency is reached, at which point, the disk frequency is set to the minimum, and then adjusted upwards until no collision band is found or the cycle is completed and avoidance is not possible. A similar procedure is followed when the range is decreasing but in this case the disk frequency is reduced by a small amount.

The following diagrams illustrates the disk frequency changes (for the sample configuration) resulting from the application of this algorithm. Results from increasing and decreasing

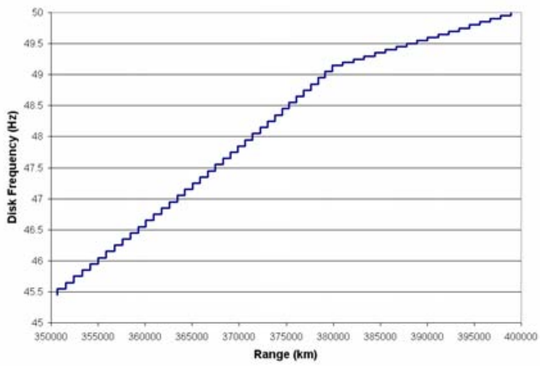

Figure 10: *Disk Frequency over increasing Lunar Target Ranges*

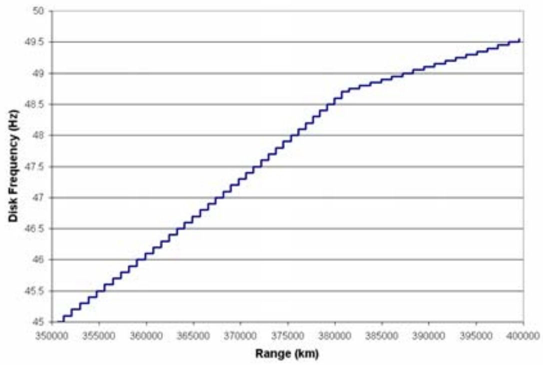

Figure 11: *Disk Frequency over decreasing Lunar Target Ranges*

ranges are shown.

Low-Medium Earth Orbit Satellite Ranges

The frequency shift patterns for increasing and decreasing distances over the low and medium earth orbit satellite ranges are shown in the figures 6 and 7. Note there are two small ranges where collision bands are unavoidable by frequency shifting for the two hole configuration used.

High Earth Orbit Satellite Ranges

The frequency shift patterns for increasing and decreasing distances over the high earth orbit satellite ranges is shown in the figures 8 and 9. There are no unavoidable collision bands.

Lunar Target Ranges

The frequency shift patterns for increasing and decreasing distances over lunar target ranges is shown in figures 10 and 11. There are no unavoidable collision bands.

Disk Design

Given a geometrical design of the disk, the disk rotation frequency can be used to minimize collision bands as described in the previous section. However can the need for frequency shifting be ameliorated by appropriate disk geometry? The number of transmit holes and the

Figure 12: *Unavoidable bands for a 1 hole disk.*

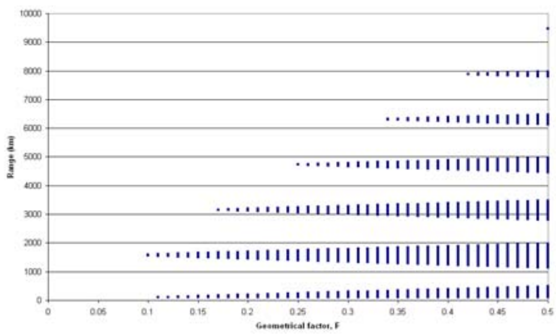

Figure 13: *Unavoidable bands for a 2 hole disk.*

geometrical factor, F, will influence the occurrence of collision bands and this is illustrated in Figure 12 for a 1 hole disk and Figure 13 for a 2 hole disk operating between 45 and 50Hz as in the previous examples. Similar diagrams can be generated for disks having three or more holes. These diagrams show the ***unavoidable*** collision bands at various ranges and various F-factors.

Clearly, more holes will result in a greater number and width of unavoidable bands over ranges up to 8,000 km. However, if the T/R disk and associated transmit hole can be designed such that $F < 0.1$ then the performance of disks with multiple holes (at least up to 3) is greatly improved. If the transmit hole radius had to be greater than, say, 10 mm, to accommodate the laser beam, then to obtain $F = 0.1$, the centre of the transmit hole would have to be greater than 100 mm from the centre of the T/R disk. Whether this is achievable would depend on other design criteria.

References:

[1] Titterton, P., “System/Usage Impact of Operating the SLR2000 at 2 Khz,”. Proceedings of the 11^{th} International Workshop on Laser Ranging, 1998, Deggendorf.