Spatial Acquisition in the Presence of Satellite Vibrations for Free Space Optical Communication Link

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Abstract

Laser communication systems offer distinct advantages over radio frequency based systems for near earth and particularly for deep space communication links. Some of the advantages are smaller size, lower power requirements and higher data rates. However, laser beam widths are very narrow and require more precise pointing, acquisition and tracking (PAT) compared to RF communication systems. In addition to imprecise knowledge of relative position and complex relative motion between the spacecraft, the problem of pointing and acquisition is complicated by vibrations present in the spacecraft. This paper analyzes the impact of satellite vibration on acquisition time and acquisition probability for a charge coupled device (CCD) based acquisition scheme. An approximation is derived for mean time to acquisition. Numerical examples of acquisition time and acquisition probability as a function of the signal-to-noise ratio are presented. The required beacon power onboard the spacecraft is also evaluated based on expected space to space link characteristics.

1. Introduction

One of the major system control functions of free space optical communication between satellites is acquisition of one satellite by another. The spatial acquisition leads to the fine pointing of the communication beam from the transmitter to the receiver. Optical systems can produce beams whose divergence can be as small as a few microradians. This leads to microradian level jitter stability requirements for closed loop tracking and pointing, together with the requirement for rapid initial acquisition. Thus, the problem of acquisition and tracking can be an important design issue for a free space optical communication link. However, simple design rules or theoretical results on expected time of acquisition for a desired probability of error and the required beacon power onboard the spacecraft are not readily available in the literature. There are two reasons for this. First, such rules will depend strongly on the signal detection scheme employed, (for example, CCD or APD based detection). Second, the problem is not well defined in the sense that the nature of satellite vibrations vary from spacecraft to spacecraft.

The CCD is increasingly becoming a popular device, due to advances in technology for optical signal detection. The advantage of using a CCD is that it can simultaneously look over a wide field of view. This permits acquisition to be accomplished in parallel, providing savings in acquisition time. in a link between a geostationary (GEO) satellite and a low earth orbiting (LEO) satellite, rapid acquisition is critical so as to enable maximum data transfer from the transmitter to the receiver during the time they can see each other in one revolution of the LEO. in this paper we consider an acquisition scheme that is CCD based and derive theoretically, the expected acquisition time as a function of the desired probability of acquisition error. The result obtained is a first order approximation. Also, an algorithm for acquisition is presented and the tradeoff between the acquisition time and the required beacon power is obtained, The analysis presented in the paper should help the system designer in making decisions on where to locate the beacon, on the GEO or on the LEO and what power levels are required for the beacon laser to achieve the desired performance in terms of acquisition time and the probability of acquisition?

Van Hove and Chan [1] have studied spatial acquisition algorithms for optical intersatellite links. They have considered direct and heterodyne reception schemes, cooperative and non-cooperative searches as well as zooming spatial acquisition searches. The results are comprehensive and cover many different scenarios. However, at that time parallel receiver technology requiring large detector arrays (= 10^4) had not yet matured, CCDs available today have array sizes 256x256 elements or larger. Also, these previous papers did not explicitly account for the influence of satellite vibrations on the acquisition time and probability of error. Barry and Mecherle [2] analyzed the effect of pointing errors on a free space optical system and derived a relationship between the RMS standard deviation of the pointing error distribution, the probability of burst error and the Airy far field beam width. The focus of their paper is on pointing and tracking and the errors involved as opposed to obtaining acquisition times. Another paper on random pointing and tracking errors by Chen and Gardner [3] also does not consider the tradeoff between acquisition time, probability of error and power requirements.

In Section 2 of this paper the effect of spacecraft vibrations on the acquisition process in a CCD-based acquisition scheme is considered. A theoretical lower bound for the acquisition time is derived that is a function of the statistical nature of the vibrational random process. A practical algorithm is presented in Section 3 and expressions relating to time of acquisition and probability of acquisition are derived, Performance analysis of the algorithm is carried out in Section 4. Beacon laser power requirements relating to the acquisition scheme are presented in Section 5 and Section 6 covers the conclusions.

2. An acquisition algorithm

The acquisition scheme considered is a parallel acquisition process, One of the satellites points a broad beam over its field of uncertainty. The receiver's field-of-view (FOV) also covers its whole field of initial uncertainty of the first satellite's position. This FOV is mapped onto a CCD array. The CCD is an array of $M_1 x M_1$ pixels and for simplicity let us assume that the received beacon gets mapped to one pixel in the array. The more general situation where the beacon energy gets distributed over more than one pixel is considered later in Section 5. If we assume that the beacon energy is large enough compared to background and other noise sources, then jitter from spacecraft vibrations is the only component left that affects acquisition time and the probability of acquisition. In this section we derive a lower bound on the expected time of acquisition based on the parameters of the jitter random process,

For the purpose of analysis the acquisition procedure that is implemented is as follows. Let the CCD array be of size $M_1 x M_1$ initially. A decision rule is implemented by which the location of the beacon spot is decided. Once the spot is located the size of the CCD window of interest is narrowed to size $M_2 x M_2$. It is in this smaller window that the spot is now searched. Since the objective is to have small time taken for acquisition, a tradeoff is made between how small the narrowed window should be relative to the expected movement of the spot on the CCD array due to jitter. Since the decision rule is implemented by searching each pixel in the window, a larger window contributes to a longer acquisition time. The expected movement of the spot in a given time interval is governed by the autocorrelation function of the jitter random process. Hence, a longer acquisition time contributes to a greater uncertainty of the spot location in the next search window. However, if the window size is made too small, there is a greater probability of losing the beacon spot altogether.

The fast zoom or narrowing down of the window size is continued until the size is small enough. We define the window size, $M_N x M_N$, to be small enough when processing of the $M_N x M_N$ is of such short duration thereby making it possible for a hand-off to the tracking loop with a very low probability, as set by the system design, of losing the spot. Thus, the acquisition time is defined to be the time interval from the initiation of the acquisition sequence to hand-off to the tracking loop, A schematic of the CCD array based detector is shown in Fig. 1,

The CCD image array integrates the image for time T_i and then the frame is transferred to CCD storage. The frame transfer involves time T_f From CCD storage a row by row vertical transfer takes place to the read out register. The transfer of one row to the read out register takes time T_t and each pixel is read in time T_r. T_s *is* the time taken to shift the pixel value through a shift register if the pixel is not read, A comparator compares the output from the pixels in the window of interest using a decision rule, (for example, the maximum count rule) and then a decision is made as to the location of the spot. In this procedure, we assume that the maximum count rule along with thresholding is used, The thesholding is done to prevent the pixel having the largest noise count from being selected, if indeed, the signal is not present,

Let the whole acquisition sequence consist of N windows, where the window size is reduced from a starting size of $M_1 x M_1$ to $M_N x M_N$. Furthermore, let us assume that the probability that the beacon spot is situated in the chosen window as q. Hence, $1 - q$ *is* the probability that beacon spot has escaped the window due to jitter. For simplicity the value of q *is* assumed to be independent of the window size, In fact, the choice for the value of q is set by the system designer and independence of q with respect to window size is not restrictive.

If the beacon spot is present in the decision window, the window size is narrowed and the next smaller window is searched, On the other hand, if the spot is not present in the chosen window, the window is enlarged and the larger window is searched. Thus, the total number of steps L_T before the hand-off to the tracking loop is a random variable. The density function of L_T cannot in general, be evaluated as it is a function of the various times involved, the sizes of the windows as well as the spectrum of the jitter random process. However, as a first order approximation the lower bound on the expected time of acquisition can be evaluated.

Let the j^{th} step of the acquisition procedure that involves scanning a window of size $M_j x M_j$ take time t_j. Let the sequence $\{M_1, M_2, \ldots M_N\}$ denote the successive reductions in the window size before the hand-off to the tracking loop. Also, let $L_j, \overline{L_j}$ denote that the spot was located in the window of size $M_j x M_j$ and that it was not located in the window of size $M_j x M_j$, respectively. Therefore, some of the sequences that lead up to a window of size $M_j x M_j$ are given by the following sequences, $\{L_1, L_2, \ldots, L_j\}, \{L_1, L_2, \ldots \overline{L_j}, L_{j-1}, L_j\}, \{L_1, \overline{L_2}, L_1, \overline{L_2}, L_1, L_2, \ldots, L_j\}$. In general, the number of steps required to reach a window of given size is a random variable whose probability density function is very hard to evaluate. Hence, to arrive at an expression for expected acquisition time we make the first order approximation that we only consider sequences of

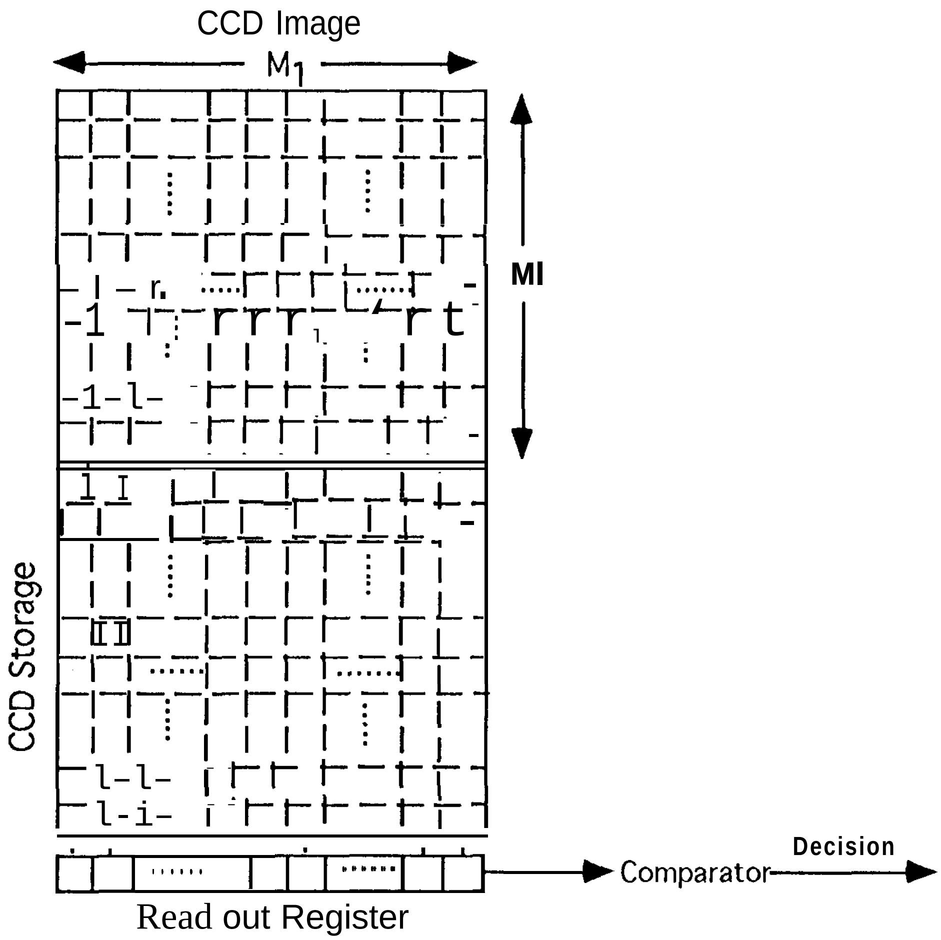

Figure 1.

the type given by $\{\ldots, L_{j-1}, L_j, L_{j+1}\ldots\}, \{\ldots, L_{j-1}, \overline{L_j}, L_{j-1}, L_j, L_{j+1}\ldots\}$, $\{\ldots, L_{j-1}, \overline{L_j}, L_{j-1}, \overline{L_j}, L_{j-1}\}$ or $\{\ldots, L_{j-1}, \overline{L_j}, L_{j-1}, L_j, \ldots, \overline{L_k}, L_{k-1}, L_k, \ldots\}$ and ignore sequences such as $\{\ldots, L_{j-1}, \overline{L_j}, \overline{L_{j-1}}, L_{j-2}, \ldots\}$, $j = 2,3,\ldots,N$. In other words, we ignore sequences where error occurs in two or more successive windows. If the probability of losing the spot in a given window is designed to be small, then the ignored sequences will occur with a very low probability and the first order approximation will hold. The expected time of acquisition is then given by the sum of the expected time to go from successful detections in one window to the next. Mathematically, the sum of expected acquisition times is given by

$$E(t_{acq}) = E_t(M_1 \to M_2) + E_t(M_2 \to M_3) + \ldots E_t(M_{N-1} \to M_N)$$

where $E_t(M_j \to M_{j+1})$, is the expected time to move from the j^{th} window to the $(j+1)^{th}$

window. Therefore, $E(t_{acq})$ can be written as

$$E(t_{acq}) = t_1 + qt_2 + q(1-q)(t_1 + 2t_2) + q(1-q)^2(2t_1 + 3t_2) + \ldots$$
$$+ qt_3 + q^2(1-q)(t_2 + 2t_3) + q^3(1-q)^2(2t_2 + 3t_3) + \ldots$$
$$+ \ldots$$
$$+ qt_N + q^2(1-q)(t_{N-1} + 2t_N) + q^3(1-q)^2(2t_{N-1} + 3t_N) + \ldots \qquad (1)$$

where the terms are as defined earlier. The above expression is rewritten convenient y as follows.

$$E(t_{acq}) = t_1 + \sum_{j=1}^{\infty} q(1-q)^{j-1}[(j-1)t_1 + jE(t_2)] + \sum_{i=3}^{N}\sum_{j=1}^{\infty} q^j(1-q)^{j-1}[(j-1)E(t_{i-1}) + jE(t_i)]. \qquad (2)$$

The expression for the time taken to search through a window is given by

$$t_1 = T_f + T_t + M_1^2 T_r + M_1 T_t \qquad \text{and}$$

$$E(t_j) = T_f + M_j^2 T_r + \left(\frac{M_1 + M_i}{2}\right)T_t + (256 - M_i)M_i T_s.\ j=2,3,\ldots,N \qquad (3)$$

where the terms are once again, as defined earlier. The frame integration time 7', of the CCD image appears only for the first window because frame integration can occur in parallel with frame transfer from CCD image to CCD storage and during the read out times for the successive windows. Since the spot may be present in any pixel of the CCD and is not known a priori, the average number of vertical transfers needed to locate the spot over many runs is taken as $(M_1 + M_j)/2$. The last term comes from the pixels that are shifted through the read out register but are not read, These are pixels that are present in the same rows as the square window in the j^{th} step. Using equations (2) and (3), the expected time of acquisition can be calculated in a CCD based acquisition system. This calculated expected acquisition time is a first order approximation as we have neglected some terms that contribute to equation (2).

In case an error occurs in the acquisition process, the beacon has to be reacquired, The expected time of reacquisition can be calculated based on the sophistication of the algorithm that is implemented. If the spot is lost from two adjacent windows, we can either start the acquisition process all over again or to enlarge the window to the next larger size. The mean time for reacquisition will depend on which of these schemes is implemented.

3. Effect of vibrations on CCD-based acquisition

In this section a method is presented to reduce the window size from the initial size of $M_1 x M_1$ to the final size before the hand off to the tracking loop. Because of jitter in the spacecraft the angle of arrival of the beacon laser is a random process. This leads to the spot moving from pixel to pixel in the focal plane, The random process has two degrees of freedom relative to the line of sight (1.0 S). 'l'he jitter process is modeled as having two components. The first component has a continuous spectrum whose bandwidth is relatively narrow around the origin, The second component is modeled as a discrete sum of random sinusoids. The jitter process is therefore written as

$$s(t) = \{x(t) + jy(t)\} + \{\sum_{i=1}^{n} A_i Cos(\omega_i t) + jB_i Sin(\omega_i t)\} \tag{4}$$

where $s(t)$ is the 2-D spacecraft jitter represented in complex form. The first complex component represents the continuous spectrum in the random process and the second complex component represents the discrete sum of random sinusoids, A_i, B_i are independent random variables that are independent of x(z) and $y(t)$. Let us also assume that $x(t) + jy(t)$ is an uncorrelated zero mean complex Gaussian process. Furthermore, we assume that $s(t)$ is wide sense stationary. Note that there is no loss in generality due to the zero mean assumption, The autocorrelation function of $s(t)$ is evaluated as

$$R_{ss}(\tau) = E[s(t)s^*(t-\tau)] = E\{x(t) + jy(t) + \sum_{i=1}^{n}[A_i Cos(\omega_i t) + jB_i Sin(\omega_i t)]\}\{x(t-\tau) - jy(t-\tau) + \sum_{i=1}^{n} A_i Cos(\omega_i (t-\tau)) - jB_i Sin(\omega_i (t-\tau))\} \tag{5}$$

where the * denotes the complex conjugate operation, Equation (5) can be simplified and is given by

$$R_{ss}(\tau) = R_{xx}(\tau) + R_{yy}(\tau) + \sum_{i=1}^{n} \alpha_i^2 Cos(\omega_i \tau) = 2R(\tau) + \sum_{i=1}^{n} \alpha_i^2 Cos(\omega_i \tau) \tag{6}$$

where it is assumed that $R_{xx}(\tau) = R_{yy}(\tau) = R(\tau)$ and $E(A_i^2) = E(B_i^2) = \alpha_i^2$. The power spectral density of the jitter random process will exhibit a continuous spectrum corresponding to $R(\tau)$ and discrete spectra corresponding to the sinusoidal component in the autocorrelation function in equation (6). The continuous portion of the spectra arise from base motion disturbances like the roll, pitch and yaw angular displacements and the discrete components arise from certain resonance frequencies in the spacecraft being triggered, for example, due to thruster firing, momentum wheel or solar array drive.

Let the distance traveled by the spot on the focal plane in time τ due to jitter be $d(t,\tau)$ such that

$$d(t,\tau) = d_x(t,\tau) + jd_y(t,\tau) \tag{7}$$

where

$$d_x(t,\tau) = x(t+\tau) - x(t) + \sum_{i=1}^{n} A_i\{Cos[\omega_i(t+\tau)] - Cos(\omega_i t)\} \quad \text{and}$$

$$d_y(t,\tau) = y(t+\tau) - y(t) + \sum_{i=1}^{n} B_i\{Sin[\omega_i(t+\tau)] - Sin(\omega_i t)\} \tag{8}$$

From equation (8) we obtain

$$E[d_x(t,\tau)] = E[d_y(t,\tau)] = 0 \tag{9}$$

and the upper bound on the variance as

$$E[d_x^2(t,\tau)] = E[d_y^2(t,\tau)] \le 2\sigma_0^2 - 2R(\tau) + 4\sum_{i=1}^{N} \alpha_i^2 = \sigma^2 \qquad \text{(lo)}$$

where $E[x^2(t)] = E[y^2(t)] = \sigma_0^2$ and R (~) is the autocorrelation of the x and y component of jitter. Since the process has zero mean the variance is equal to the mean squared value. Thus, the distance moved by the spot in the x *and y*- directions in time τ is a Gaussian random variable with mean zero and the upper bound on the variance given by equation (1 O). The probability density function of the distance moved by the spot can be expressed as

$$f_{D_x,D_y}(d_x,d_y) = \frac{1}{2\pi\sigma^2} e^{-\frac{d^2_x + d^2_y}{2\sigma^2}} \qquad -\infty < d_x, d_y < \infty. \qquad (11)$$

Given the probability density function of the beacon spot motion in equation (11), a systematic reduction of window size in each step of the acquisition scheme can be devised. The procedure used to reduce the size of the window size is follows. Let the j^{th} step of the acquisition process take time t_j. 'hen, using equations (9- 10), the mean and variance of the spot movement in time t_j is calculated to be

$$E[d_x(t,t_j)] = E[d_y(t,t_j)] = O \text{ and}$$

$$E[d_x^2(t,t_j)] = E[d_y^2(t,t_j)] = 2\sigma_0^2 - 2R(t_j) + 4\sum_{i=1}^{N} \alpha_i^2 = \sigma_j^2 \qquad (12)$$

The probability that the spot moves by more than m_j in time t_j is therefore:

$$P(\varepsilon) = 1 - \int_{-m_j}^{m_j} \int_{-m_j}^{m_j} \frac{1}{2\pi\sigma_j^2} e^{-\frac{d^2_x + d^2_y}{2\sigma_j^2}} dd_x dd_y \qquad (13)$$

where $P(\varepsilon)$ is the desired error probability. The solution to equation (13) gives a square window of length $2m_j$ within which the spot is expected to remain for the chosen probability of error. Hence, we can chose the next window size to be *2mjx2mj.* **Since** $2m_j$ may not be an integer the next higher odd integer value, M_j is chosen as the length of the square window. The selection of an odd integer helps in placing the location of the spot in the j^{th} step at the center of the window for the next search. This process of window size reduction is carried out until the size of the window reaches a pre-decided number that can be handled by the tracking loop. Note that as the window size reduces the variance of the spot movement also decreases due to lesser search time, which is the sum of frame transfer time and the pixel read out time, The manner in which the variance reduces as a function of frame processing time is given by equation (12). This reduction in variance helps in constructing a window of even smaller size for the next step.

4, Performance simulation of the acquisition algorithm

The initial CCD array is chosen to be of size 256x256 pixels. The final size of the array that is handled by the tracking loop is 5x5 pixels. The continuous portion of the spectrum is modeled as an exponential spectrum, The shape and data for the discrete components in the spectrum are obtained from [4]. The continuous spectrum has a 3 dB bandwidth of 5 Hz and the three discrete frequencies chosen correspond to 2Hz, 10 Hz and 300 Hz respectively. The RMS values corresponding to the power associated with these values are also obtained from [4]. The initial field of uncertainty is 1 mrad x 1 mrad, which is mapped to 256x256 array, Therefore, each pixel corresponds approximately to 4 μ rad x 4 μ rad field of view. The peak value of the Power Spectral Density is taken as 240 μ rad^2. The three discrete components have mean square jitter values equal to 1 μ rad^2, 4 μ rad^2 and 16 μ rad^2 respectively. The autocorrelation function and the power spectral density of jitter is then given by

$$R_{ss}(\tau) = 90e^{-6|\tau|} + 2Cos(600\pi\tau) + 0.5Cos(20\pi\tau) + 0.125Cos(4\pi\tau),$$

$$S_{ss}(f) = \frac{30}{1+(\frac{\pi f_v}{3})^2} + 2\delta(f-300) + 0.5\delta(f-10) + 0.125\delta(f-2).\ f>0 \qquad (14)$$

The values for T_i, T_f, T_r, T_t, T_s are chosen to be 356 μ see, 144 μ see, 1 μ see, 1 μ sec and 0.1 μ sec respectivel y. The algorithm presented in Section 3 is implemented, The result of the simulation is shown in Table 1.

Window Error Probability, q	10^{-7}	10^{-6}	10-4
	Window size		
Step 1	256x256	256x256	256x256
Step 2	45x45	43x43	35x35
Step 3	21X21	19X19	1 5X15
Step 4	11X11	9x9	5x5
Step 5	5x5	5x5	

Table 1. Sequence of window size reductions to reach a 5x5 window for three different error probabilities (P(c)).

It is seen that the minimum number of steps required to reduce the window to tracking loop requirements is 5 for error probability y equal to 10^{-7} and 10^{-6} and 4 for error probability equal to 10^{-4}. This minimum number of steps is achieved when the signal to noise ratio in the detector is very large, The noise in the pixels is assumed to be Gaussian distributed and the maximum count rule followed by thresholding is used to discriminate between signal and noise. As the signal to noise ratio falls the number of steps before hand-off to tracking will increase, However, the window size in each step will be one of the values given in the table for a specific error probability.

The probability that a successful hand-off to the tracking loop occurs in N steps, equal to the number of window size reductions is given by

$$P(N\ step\ Acquisition) = [1 - P(\varepsilon)]^{N-1} \prod_{i=1}^{N} Pi \tag{15}$$

where the error probability due to jitter in each window is assumed identical and equal to $P(\varepsilon)$ and the $P_i s$ represent the probability that the pixel containing the beacon signal is correctly identified in each window. $P_i s$ are governed by the signal to noise ratio in the receiver. To obtain a desired probability of a N step acquisition the beacon signal must have the appropriate power amidst other noise sources.

Choosing $P(\varepsilon)=10^{-7}$, the five step acquisition process is implemented. The total time taken for a successful five step acquisition scheme is 72 msec. Figure 2 shows the probability of error in acquisition versus the required beacon signal photon count for various background count levels. It is seen from the figure that the lower bound on the total error probability in the 5 step acquisition is $1 - (1 - 10\text{-}7)^4 \approx 10^{-6.4}$. This would be the ideal case for large signal to noise ratios, The error is due to jitter alone where at each window the error due to jitter is equal to 10^{-7}.

For a typical space to space link the background varies from the best case value of zero to the worst case value of 1()()0 photo counts/integration time, The worst case number of 1000 counts is approximately equal to peak Earth albedo seen from the GEO satellite. The CCD readout noise is taken as 100 photo counts/pixel, It is noticed from Figure 2 that a signal count of 600 counts will achieve the lower bound for all background noise conditions, The signal count required is as low as 300 counts when the background count is zero or the receiver does not face earth shine. Also, it is seen from the figure that depending on the noise level, the error probability rises rather steeply below a certain signal power.

The lowest time to acquisition of 72 msec will obviously be obtained if the 5 step acquisition sequence is implemented and is successful. However, because there is a finite probability of error, the acquisition may require more steps, In the previous two sections we discussed how the errors can be corrected by going back to the previous larger window and locating the spot again. That is a good rule when the number of steps involved is very large or the time taken for each step is very high. In a five step sequence where the number of pixels of interest reduces by two orders of magnitude from the first to the second step a simpler procedure can be implemented by going back to the beginning and starting all over again. The expected acquisition time for this approach is derived as follows. Let the five step process take time $T_{acq}^{(5)}$ (which in this case is 72 msec), then if the probability of successful acquisition is Q, which is determined by the jitter in each window as well as signal-to-noise (SNR) considerations, then the expected time of acquisition is given by

$$E(T_{acq}) = QT_{acq}^{(5)} + 2Q(1-Q)T_{acq}^{(5)} + 3Q(1 - Q)27acq\%, \ ,.$$

$$\frac{T_{acq}^{(5)}}{Q} \tag{16}$$

Figure 3 is a plot of the expected acquisition time versus the signal count for the various background count levels. It is seen that the lowest time for a acquisition is reached for all background conditions with a signal count of approximately 300/pixel. At this value the SNR is large enough that error in acquisition is due to jitter alone. As the signal count decreases the expected time of acquisition rises sharply and will approach infinity in the limiting case as the signal count tends to zero.

5. Beacon power requirements

The expected acquisition time and the probability of acquisition in a specified time depend on the signal photon count per pixel as seen from Figures 2 and 3. Also, it is noticed from the figures that the bounds on the acquisition and error probability are approached quite fast once the signal count exceeds a certain value depending on the background noise. Thus, it will be illustrative to determine the power specifications for the beacon laser on the spacecraft, Assuming a uniformly illuminated broad beam for the beacon, the power collected at the receiver, P_R, *is given* by

$$P_R = \frac{\eta P_b A_R}{\pi D^2 \alpha^2} \tag{17}$$

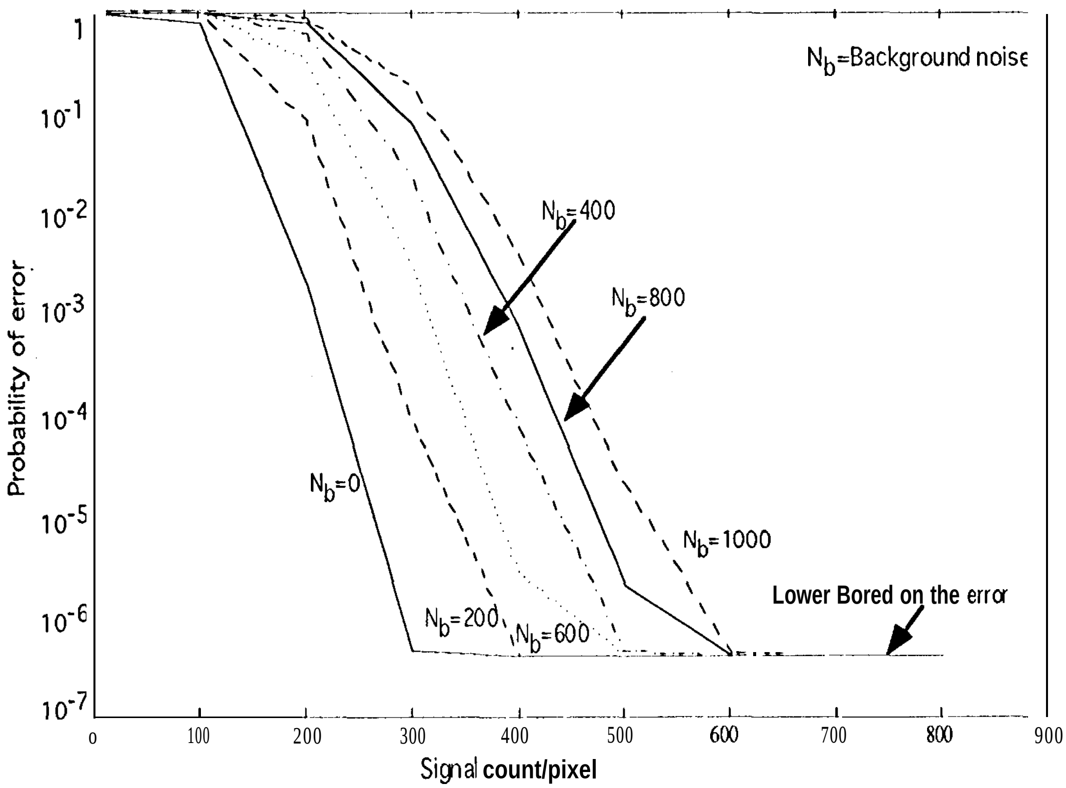

Figure 2. Plot of the probability of error in a 5 step acquisition vs. required signal count.

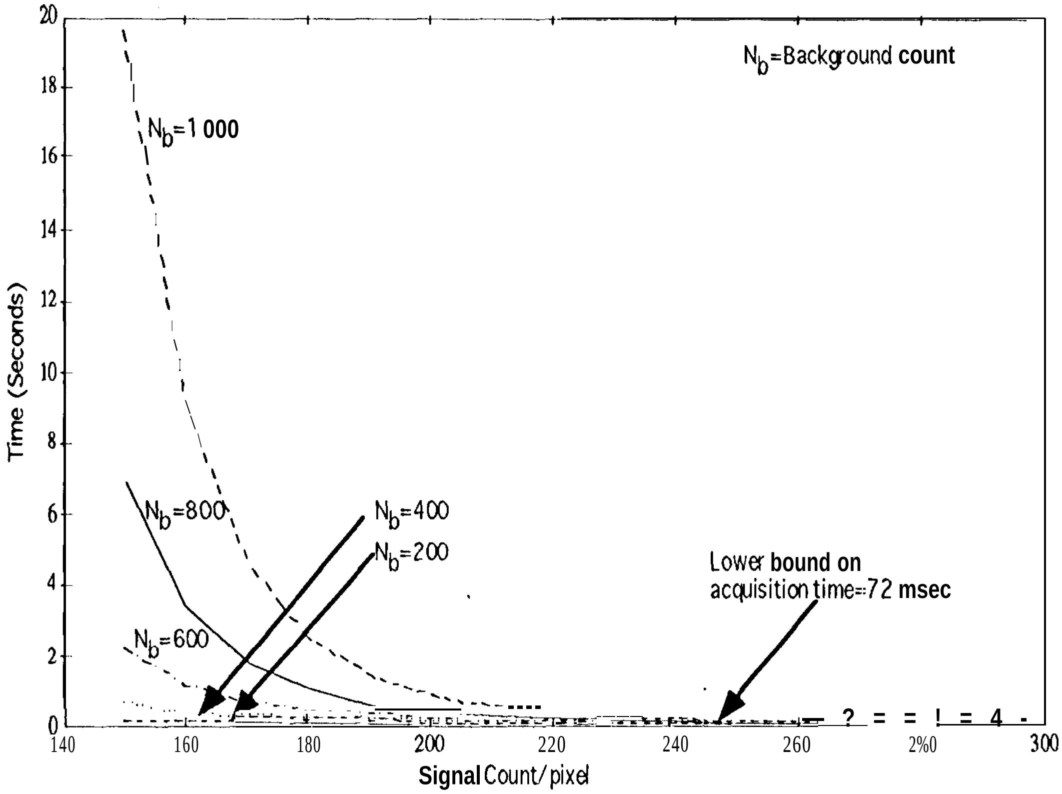

Figure 3. Plot of expected value of acquisition time versus required signal count.

where η is the optics efficiency, P_b is the beacon laser power, A_R is the collecting area of the receiver optics, D is the distance between the satellites and α is the beam width.

From Figures 2 and 3 it is seen that the bounds on acquisition probability and acquisition time are reached for received photo count of 300/pixel per integration time of 356 μ sec when the background is noiseless and 600/pixel per integration time for the worst case background value of 1000 counts/pixel. Thus there is a 3 dB increase in the required signal power going from the best case to the worst case. Choosing η =0.1, P_R=300 photons/pixel, the aperture size of the receiver as 20 cm in diameter, D=40,000 km and α= 1 mrad the required beacon power is $\approx$0.5 v?.

However, it is important to note that the analysis assumes that all the beacon energy is contained only in one pixel. In practice, the beacon image can occupy an area the size of 4 pixels. To account for this "spread the required beacon power must be increased to 2 W for the best case noise scenario and to 4 W for the worst case noise scenario, This number is useful to the designer in choosing the LEO or the GEO to place the beacon in: Placing the beacon on GEO means that the background noise will be negligible as the LEO looks for the beacon assuming no sun, moon or stray light. A continuous wave laser of 2 W is required for this. Placing the beacon on the LEO implies that the GEO will have the earthlit background during daytime. If continuous operation is desired then the required beacon continuous wave laser power is 4 W. In practice, it is important to provide a margin for the beacon laser power required, Providing a 3 dB margin leads to a beacon power requirement between 4-8 Watts.

The tradeoff is with the cost of the launch. Although a higher powered laser, which amounts to a higher mass is required on the LEO, the cost associated with that may be lower than sending a lower powered laser to a satellite at the GEO orbit, This tradeoff has to be judged against the system design considerations,

6. Conclusions

The analysis in this paper shows that a rapid acquisition of one satellite by another is possible for a free space optical communication link with currently available technology. It is shown that using a continuous wave beacon laser between 4-8 W depending on the background noise level, the expected acquisition time is as low as 72 msec and the error probability associated with acquisition during this time is $\approx 10^{-6.4}$. The model assumed due to satellite vibrations is similar to those empirically observed in existing satellites, Although we used a first order approximation in deriving the expected time for acquisition and the probability of error in Section 2, no approximations are used in obtaining Figures 2 and 3. These figures represent the exact values given the underlying model for the vibration, The results presented in the paper provide a method to thes ystem designer to evaluate the tradeoff between the acquisition time, probability of error, beacon laser power and where to place the beacon.

Acknowledgment

The research described in this paper was carried out at the Jet Propulsion Laboratory, California institute of Technology for the National Aeronautics and Space Administration. The first author would like to thank the National Research Council for awarding a Research Associateship that enabled him to work at the Optical Communications Group at JPL. We would like to express our thanks to Dr. Hoomayun Ansari for the many discussions we had and to Dr Hamid Hemmati and Dr. James Lesh.

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