Poisson Filtering of Laser Ranging Data

by

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The filtering of data in a high noise, low signal strength environment is a situation encountered routinely in lunar laser ranging (LLR) and, to a lesser extent, in artificial satellite laser ranging (SLR). The use of Poisson statistics as one of the tools for filtering LLR data is described first in a historical context. The more recent application of this statistical technique to noisy SLR data is also described.

Introduction

Routine LLR operations began at McDonald Observatory in August, 1969 as a part of the NASA Apollo Lunar Ranging Experiment (LURE), using the newly-commissioned 2.7-m astronomical telescope to range to the retro-reflector array placed upon the lunar surface by the Apollo 11 astronauts. During the next several years, additional arrays were left on the moon during the Apollo 14 and Apollo 15 missions, and by two Soviet unmanned soft landing vehicles. Routine LLR operations continued on the 2.7-m telescope until the mid-1980's when these operations were transferred to the dedicated 0.76-m aperture McDonald Laser Ranging Station (MLRS).

It is important to realize that the return signal strength ratio, neglecting all parameters except distance, for a near-Earth artificial satellite and the Moon is something like 3×10^{12}. Thus, it is more than a trillion times more difficult to range to the Moon than it is to range to, say, Ajisai. In the extremely low signal strength environment of LLR it was (and continues to be) necessary to operate largely at the single photon-electron level. However, this means that a very large number of "volunteer" photons from any number of background noise sources may trigger the detection electronics, even though very narrow spatial, spectral and temporal filters are routinely employed in the receive package. Since all incoming photons are indistinguishable from one another, identifying the valid returns from the moon has been a difficult task. From this experiment's inception, the reliance on statistical filtering methods, in addition to the physical ones, had been always assumed.

The application of Poisson statistics to the LLR data filtering problem provided an effective tool for dealing with high-noise, low signal data. The technique has now been expanded and adapted to handle marginal SLR data as well and has proven to be especially effective when applied to data from single or low-multiple photo-electron systems during daylight passes and data from all stations when they are ranging more difficult targets like Etalon-1, Etalon-2, and MP-2. Figures 1 and 2 show samples of noisy data, displayed by MLRS onsite software, for which the Poisson technique is required.

Background

Let us consider the mathematical concept of the Poisson distribution, which gives the probability that a certain integer number, k, of unit rate random events from a population, n, will occur in a given interval of time, x, within some total interval of time. The operative equation is:

$$P(k) = \frac{x^{[k]} e^{-x}}{[k]!}$$

where [k] is the largest integer less than k. For x large enough, this function has a bell shape comprised of many rectangular steps. Multiplying the computed probability by the number of bins in the entire sample time gives the number of bins which contain exactly k events.

In a descriptive sense, Poisson statistics states that if one has "n" observations of some independent variable defined over some range of "m" bins of uniform width, and if those observations are random, one can compute, in a statistical sense, how many of those bins will contain exactly k observations. For example, for some specific experiment of, say, 16 independent observations of some value, one might compute from the above equation that 3 of the bins will be empty, 4 of them will contain exactly 1 observation, 3 of them will contain exactly 2 observations, 2 of them will contain exactly 3 observations, and no bins will contain 4 or more observations. Then, if one looks at the actual histogram of measurements and finds that one of the bins contains 8 of the 16 observations, one might safely assume that those observations are indeed not from a random distribution and that something systematic has occurred. In the case of LLR or SLR observations, where the measurement is an (o-c) range residual, it is assumed that the bin (or bins) containing a statistical excess of observations are probably valid returns from the target or the result of some systematic effect in the ranging equipment. As another example, figure 3 represents the statistics from the lunar data in figure 1. The predictions indicate that there should be no bins with more than 21 points. One bins has 22 points, which is probably not significant, but there is another bin with 47 points, which is significant. That bin contains the lunar data.

This technique is routinely applied to the filtering of McDonald Observatory LLR data and is fully described in "Laser observations of the Moon: Identification and construction of normal points for 1969-1971 by Abbot, Shelus, Mulholland and Silverberg (Astron. J., Vol. 78, No. 8, pp 784-793, October, 1973).

Current state of affairs

In the routine application of the Poisson technique to data filtering it must be noted that, in order to have the best possible chance of isolating signal from noise, one should use the narrowest bin width possible, keeping in mind at all times, of course, the quantity being measured. Narrow bins will maximize the signal to noise ratio since, in a narrow-bin environment, a relatively small number of noise photons will be found in any one bin. Further, it is absolutely required that the data be flattened before a histogram is formed, i.e., trends must be removed from the data as much as is possible, so that signal will not "spill over" into many adjacent bins and, again, be lost in the "noise". This problem has been addressed in a straightforward way in the current data screening implementation at the MLRS, as shown in figure 4. All bins are scanned sequentially through a predetermined range of slopes, the plan being that the signal will appear at a significant peak at a slope that matches the inherent slope of the data. This technique is especially important for LLR data when signal strength is low and for SLR data when orbits are not well known. Of course, in altering the slope of the data, one must take care to exclude, or compensate for, those bins which will be incomplete due to clipping. In its present implementation at the MLRS, the Poisson screening software also allows multiple segments of a pass, or a run, to be treated separately. This handles the natural change in residual slope over an extended observation session.

Although personnel at the MLRS are now applying the Poisson filtering technique for both lunar and artificial satellite data, the LLR and SLR screening systems are somewhat different. Both systems provide user interaction to allow the selection of the parameters of the Poisson fit, placement of the time bins, maximum and minimum slopes, and a maximum and minimum residual for data to be accepted as "real". For lunar data, we employ fairly strict limits on acceptable slopes and allowable residuals. Earth rotation and polar motion are major contributors to slope and residual for lunar data, so the earth orientation predictions are kept as fresh as possible. Further, there is considerable latitude in selecting time bins to reflect the observed clumping of MLRS LLR data. Ultimately, the Poisson filter is relied on to provide the LLR data compression, i.e., normal pointing, software with a set of acceptable data.

For the SLR case, the Poisson algorithms serve as a preliminary filter and suggest to the polynomial fitting algorithms in the normal pointing packages a set of data with which to start. The polynomial fit, in its job, can then return previously rejected data back into the fit or remove data suggested to it by the Poisson filter, if either of these tasks are warranted. Also, the polynomial fit, working on the entire pass, can pull in data that might be missed or misinterpreted when the Poisson filter was working on only shorter segments of a pass.

The independent time segments, into which an SLR pass is broken, allow the software to follow changes in slope during a pass and minimize the effect of anomalous distributions of data in short segments. We are examining the desirability of having several software checks that require the slopes and average O-C residuals to be smoothly varying over the pass. However, in the cases where there are breaks in the data and other unusual distributions, this may not be practical.

Results

In the case of LLR data, the presently implemented Poisson filtering technique works well, especially with a bit of interactive help from the user, although, in marginal cases, it would be preferable to use all runs taken over a lunar pass to aid in the filtering . This particular extension is now being examined. As time permits we are also pursuing more elaborate filtering techniques such as jack-knifing and bootstrapping to see if they hold merit.

In the case of SLR, the technique has been used successfully at MLRS for about a year now. In that time our experience has been that the combination of the Poisson filter and the polynomial fit produces good results virtually all of the time. The marginal cases can usually be satisfactorily processed, after the fact, by altering some of the parameter of the Poisson fit or by eliminating from consideration extremely noisy parts of the pass. Of course, most of the anomalies usually occur with weak passes, especially Etalon-1, Etalon-2 and ERS-1. The Poisson filter algorithms are being upgraded so that each satellite uses a parameter set tailored to it. Tests indicate that this will allow successful batch processing of virtually all passes that previously required special handling. Also, an interactive tool similar to the Lunar Data Editor is being developed to help the observing crews to quickly recover passes that were improperly processed. The Laser Tracking Network operated by the Bendix Field Engineering Corporation will soon install the MLRS "batch" Poisson code into their processing software.

Conclusion

The Poisson filtering technique has proven itself to be an extremely valuable tool for both LLR and SLR operations at the MLRS. This technique is being optimized for each ranging target, and in the future provision will be made for routine, near-real-time observing crew interaction with the filter. In addition, new filtering techniques such as jack-knifing and bootstrapping will be evaluated as to suitability for laser ranging data filtering.
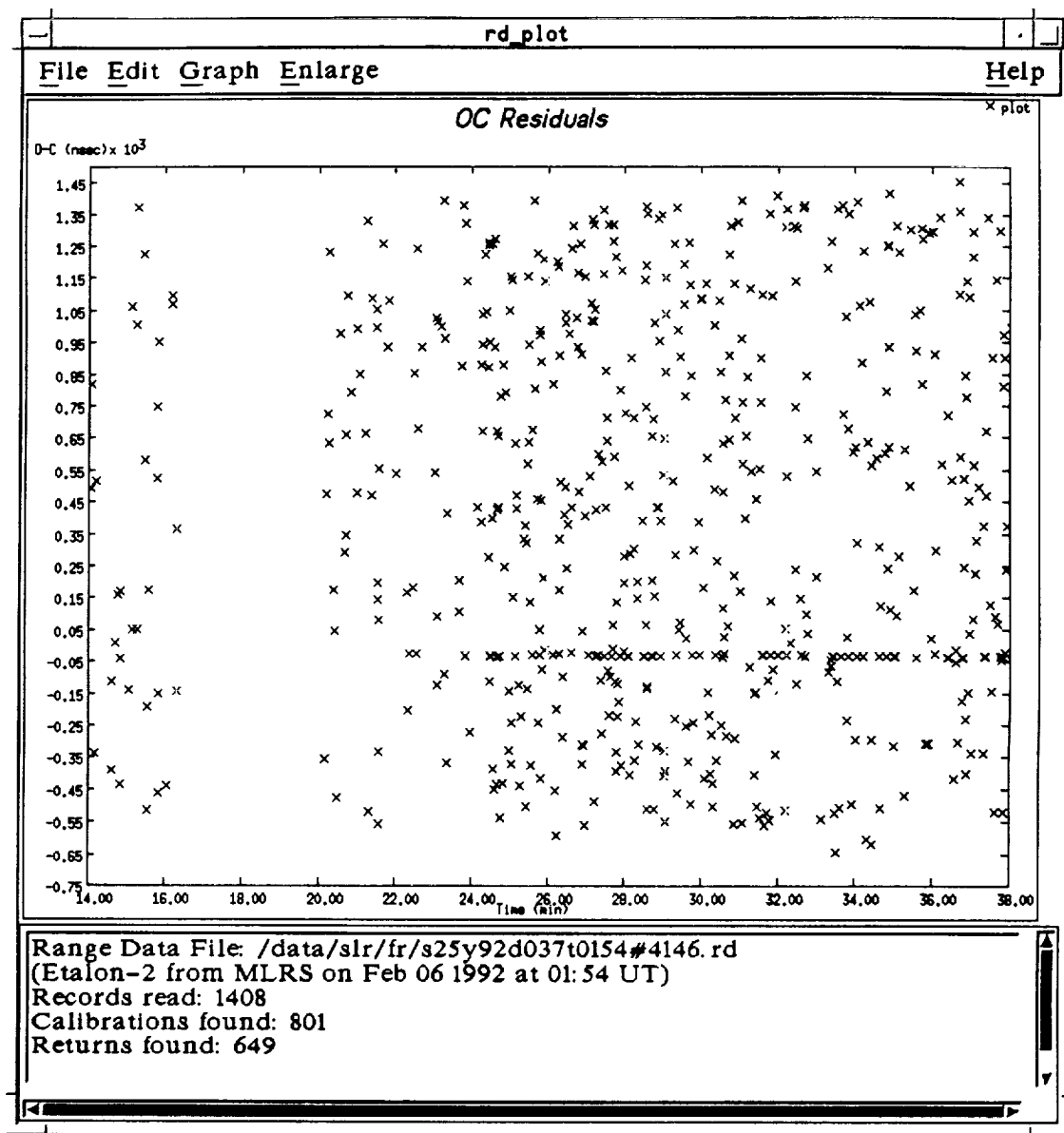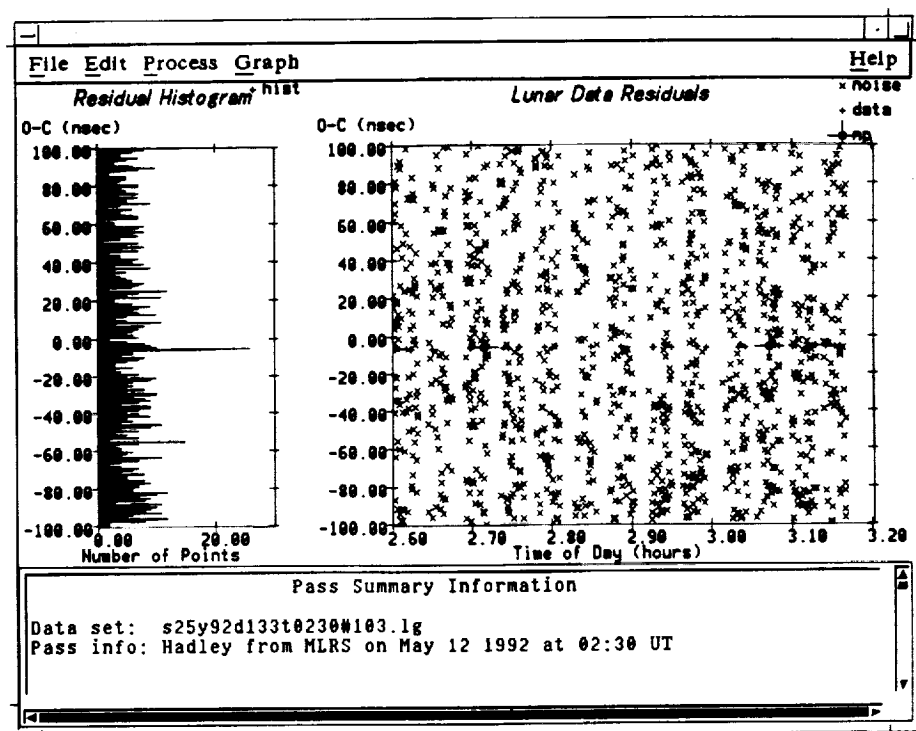
Figure 1 - Noisy Artificial Satellite Data

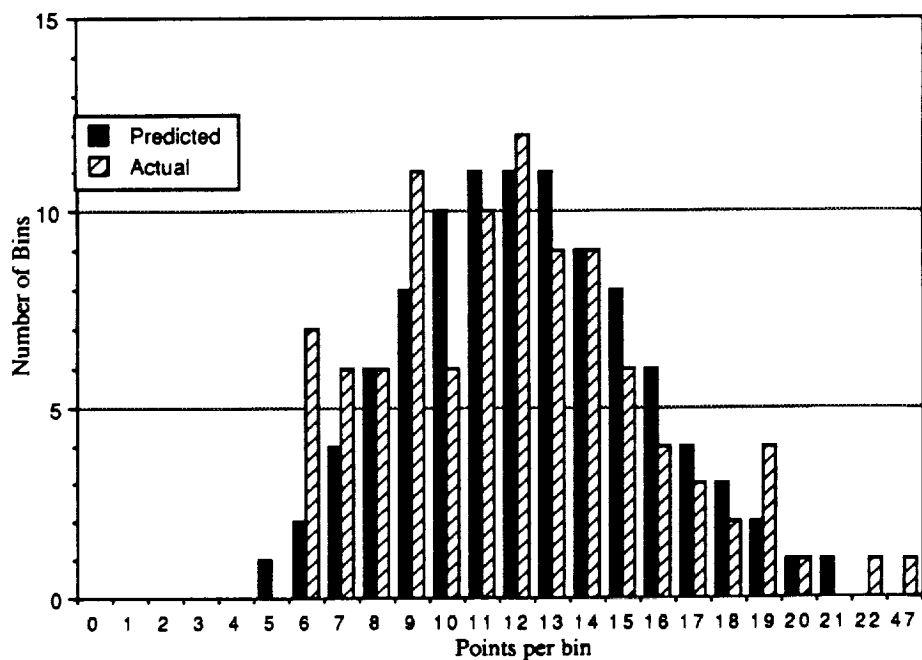Residual Histogram⁺ ʰⁱˢᵗ   Lunar Data Residuals   × noise
                                                                        + data

Figure 2 - Noisy Lunar Data

Figure 3 - Poisson Statistics for Sample Lunar Run

range residual

time into pass

Bins for Poisson analysis, sloped to match data. Histogram results from 2 bins being selected at a time

Bins at improper slope, result in no significant bins.

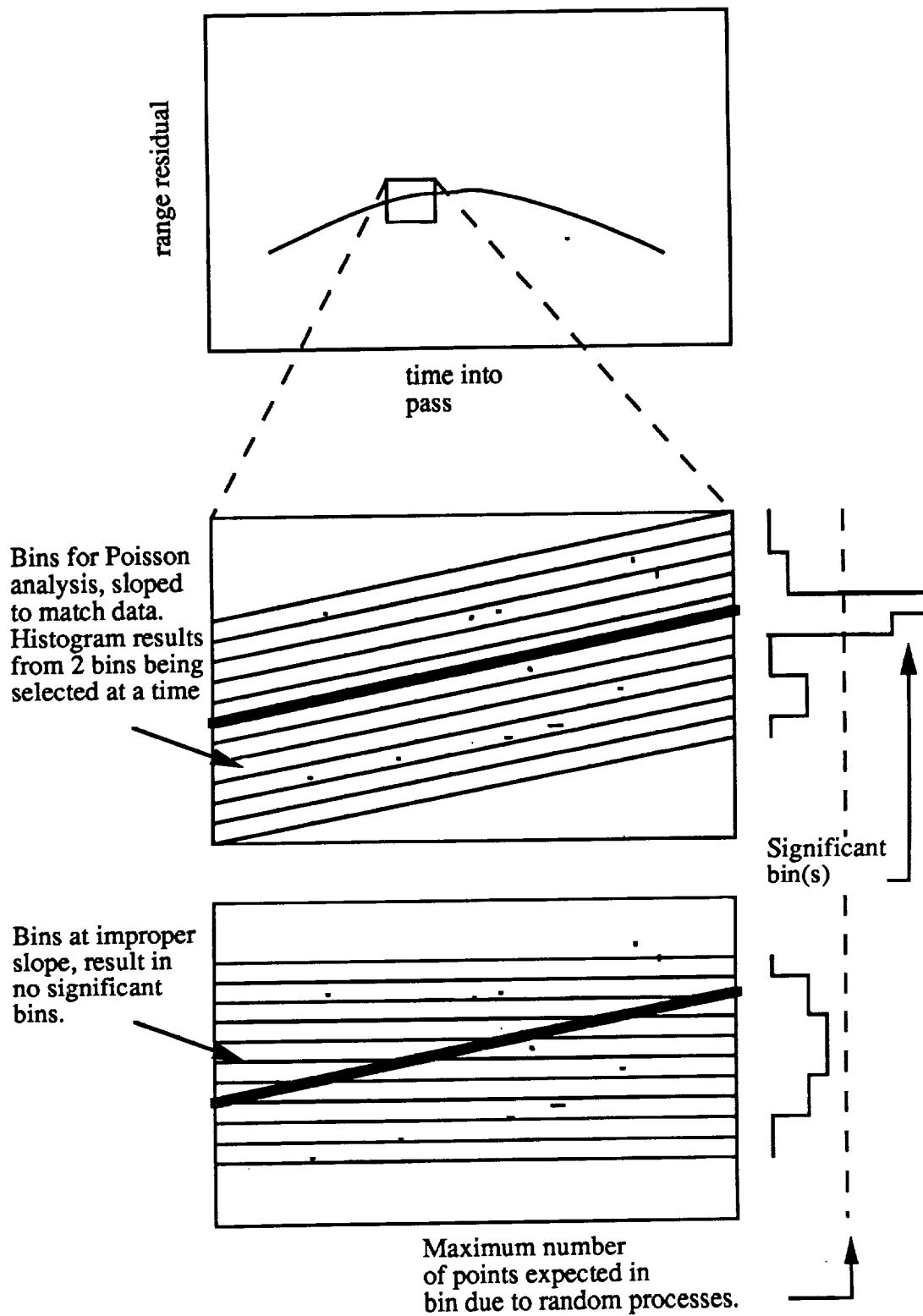Significant bin(s)

Maximum number of points expected in bin due to random processes.

Figure 4 - Effect of Tilting Bins