# *Impact of Receiver Deadtime on Photon-Counting SLR and Altimetry during Daylight Operations*

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# *Overview*

- **Background Noise Sources**
- **Photon-Counting Detectors and Limitations**
- **Solar Noise Models for:**
  - **SLR (e.g. NGSLR/SLR2000) or Transponders**
  - **Altimetry (e.g. 16 channel Photon-Counting Cross Track Channel Lidar proposed for ICESat-II)**
- **Pre-Detection Filtering Techniques**
- **Summary**

# *Background Noise Sources*

* Detector Dark Counts (day or night)
  – ~30 kHz (whole MCP/PMT tube)
  – ~2 kHz per channel (individual anode)
* Solar Scattering off surface (day only)
* Solar scattering off intervening atmosphere (day only)
* Laser backscatter from instrument optics and local atmosphere, especially in monostatic systems such as NGSLR (day or night, time-dependent)
* This presentation will focus on the solar background during daylight operations.

# *Impact of Solar Background Noise on Photon Counting Rangers and Altimeters*

**High solar background rates:**

★ **Can thwart signal detection in detector/receiver systems with receiver recovery times, $\tau_d$, comparable to the mean time between solar photon arrivals. The background rate must satisfy:**

$$\dot{n}_b << \frac{1}{\tau_d}$$

★ **Reduce the signal contrast\* (similar to Signal-to-Noise Ratio in multiphoton lidars) making the satellite or surface returns more difficult to identify during post-detection filtering**

★ **In Microchannel Plate PMT's, high background rates**
  – **Can cause the microchannel plates to temporarily exceed their current limits (saturation) and reduce responsivity.**
  – **Can reduce microchannel plate photomultiplier lifetime by extracting excessive charge from the microchannels.**

★ **Add significantly to onboard data storage and/or communications bandwidth unless the noise can be successfully filtered pre-detection or edited out via near real-time post-detection algorithms.**

# *Photon-Counting Detector Options*

* **Passively Quenched Single Photon Avalanche Diode (PQ-SPAD)**
  - **Recovery Time: ~1600 nsec**
  - **Maximum Count Rate: < 60 kHz (<10% data loss)**
* **Actively Quenched Single Photon Avalanche Diode (AQ-SPAD)**
  - **Recovery Time: ~50 nsec**
  - **Maximum Count Rate: <2 MHz (<10% data loss)**
* **Microchannel Plate Photomultipliers (MCP/PMT)**
  - **Recovery Time: <2 nsec**
  - **Maximum Count Rate: < 500 MHz BUT**
  - **Photocathode Saturation Current: 10 nA (<64 GHz)**
  - **Microchannel Plate Saturation Current: 200 nA (<4.3MHz for G=3x10$^{5)}$.**
  - **Maximum Count Rate: < 4.3 Mhz (MCP current-limited not recovery time limited; no data loss)**
  - **50% Responsivity Lifetime: ~1 Coulomb/cm$^2$ of anode area (based on Hamamatsu measurements on single tube; additional lifetesting being initiated at Sigma)**
* <u>**In all cases, the range receiver dead time should  preserve the detector speed.**</u>

# Sigma 50 Channel Amplifier/ Comparator Board

- Channel deadtime measured to be less than 2 nsec and preserves fast MCP/PMT response.
- Thus, each anode (pixel) can see multiple objects separated by as little as one foot (30 cm) in a single pulse return
- Enhances daytime ops as well as fog and tree canopy penetration
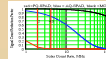

Bottom View


Top View


Signal Input

Comparator Output

2 nsec
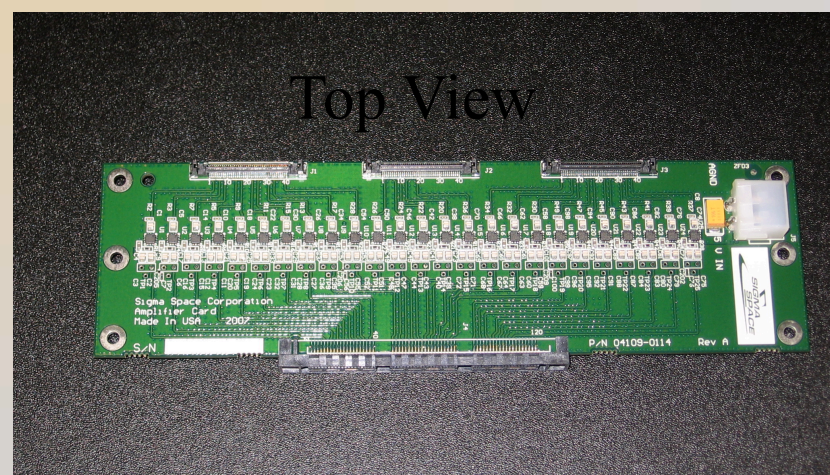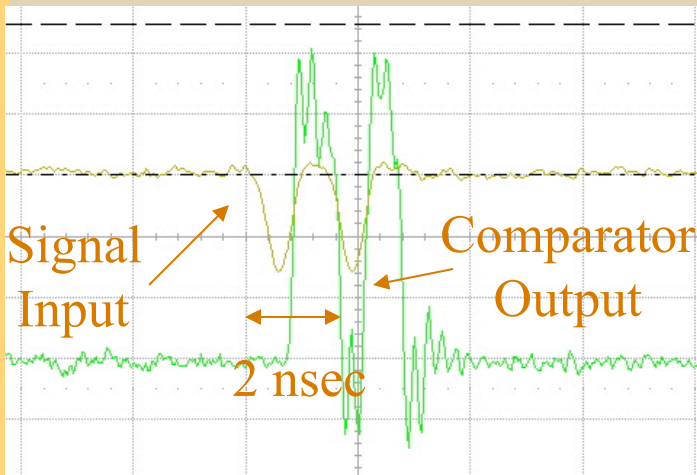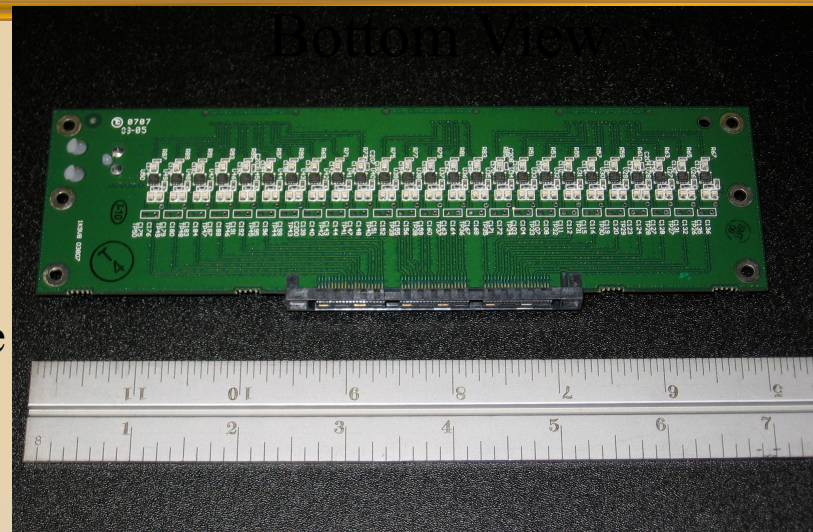
# *Signal Count Reduction vs Receiver Recovery Time*

From Poisson statistics, the solar photon count rate will cause the mean signal count to be reduced by a factor

$$RF = \exp\left(-\dot{n}\tau_d\right)$$

Where

$\dot{n}$ is the solar count rate and

$\tau_d$ is the receiver recovery time

# *Four Pre-Detection Noise Filters**

* **<u>Spectral</u>** – choose narrowband filters trading off between bandwidth, optical throughput, and added operational complexity (e.g. GLAS 25 pm etalon)

* **<u>Spatial</u>** – use minimum receive FOV consistent with transmitter divergence, telescope image quality, and transmit/receive co-boresight stability.

* **<u>Temporal</u>** – use range gates to only accept returns from the region of interest and reject other regions.

* **<u>Amplitude</u>** – choose receiver detection thresholds to eliminate background "false alarms" in high SNR systems (not generally available to photon-counting systems except for eliminating low-level electronics noise but there is a post-detection equivalent.)

*Reference: J.J. Degnan, "Millimeter Accuracy Satellite Laser Ranging: A Review", in <u>Contributions of Space Geodesy to Geodynamics: Technology</u>, D. E. Smith and D. L. Turcotte (Eds.), AGU Geodynamics Series, Volume 25, pp. 133-162, 1993.

# Solar Count Rate Model*
# (NGSLR Example)

$$\dot{n} = \frac{\eta_q \eta_r}{h\nu} \frac{N_\lambda (\Delta\lambda) \Omega_r A_r}{4\pi} \left\{ \sec\theta_t T^{\sec\theta_t} \left[ \frac{1 - T^{\sec\theta_s - \sec\theta_t}}{\sec\theta_s - \sec\theta_t} \right] \right\} \quad \text{General Case}$$

$$\cong \frac{\eta_q \eta_r}{h\nu} \frac{N_\lambda (\Delta\lambda) \Omega_r A_r}{4\pi} \left\{ T^{\sec\theta_t} \ln\left( \frac{1}{T^{\sec\theta_t}} \right) \right\} \longleftarrow$$

Approximation valid for T>0.6 and $\theta_t$ <70º.

$\eta_q$ = detector counting efficiency =0.28

$\eta_r$ = receiver optical efficiency =0.4

$h\nu$ = laser photon energy = 3.74 x $10^{-19}$ J

$N_\lambda$ = Exoatmospheric Solar Irradiance = 0.2 W/m²-Aº-ster @532 nm

$\Delta\lambda$ = spectral filter bandwidth = 3Aº

$A_r$ = telescope receive area = 0.126 m²

$\Omega_r$ = πω² = receive solid angle in steradians

$T$ = one-way atmospheric transmission at zenith at laser wavelength

$\theta_s$ = solar zenith angle

$\theta_t$ = target zenith angle
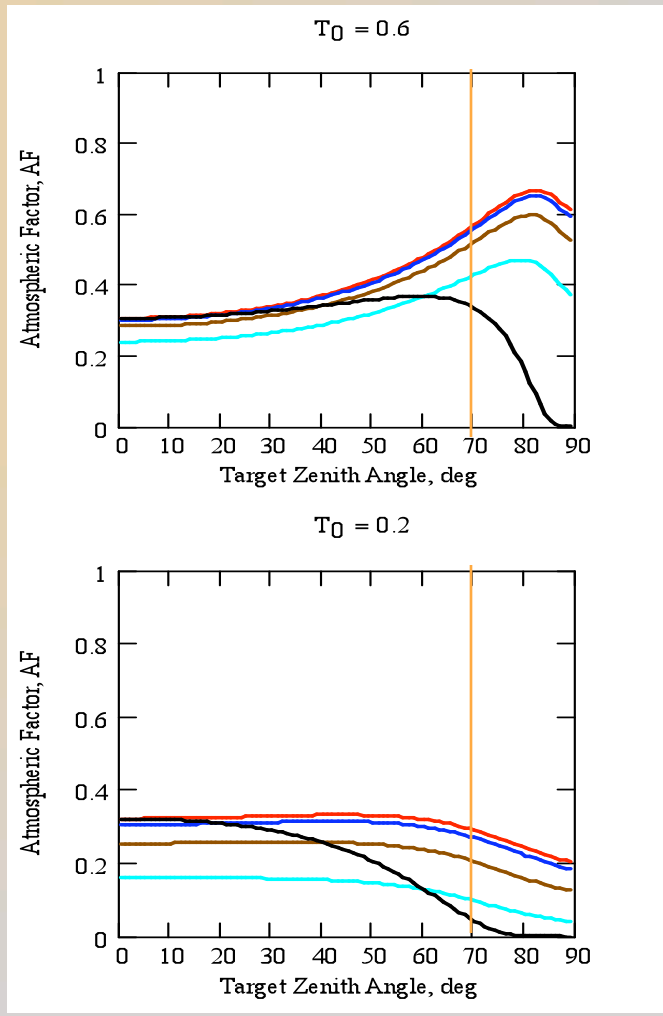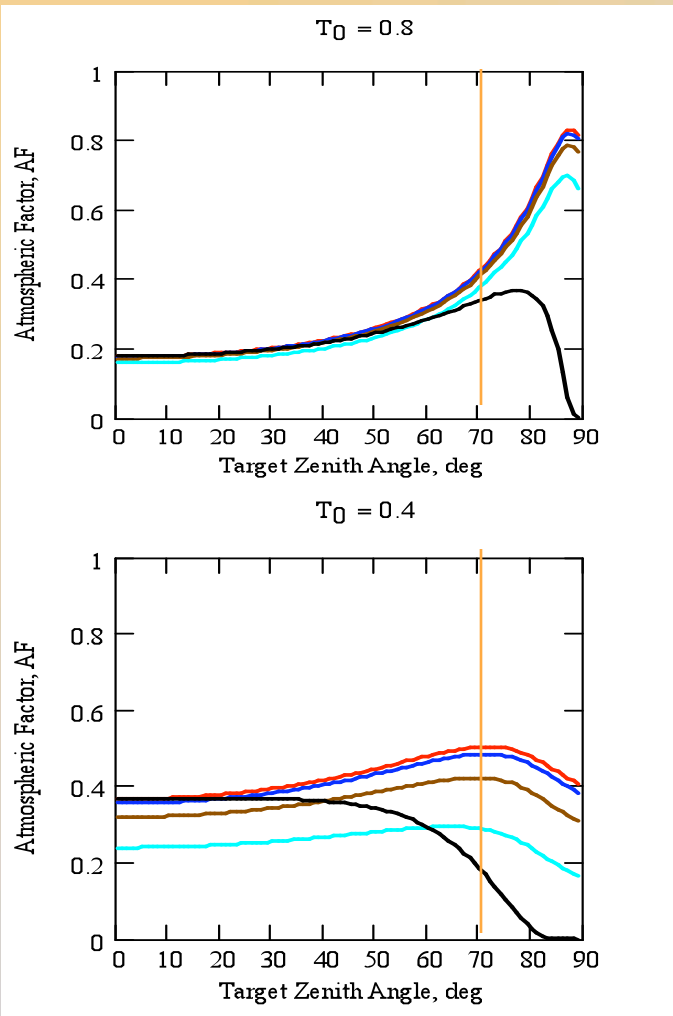
**\*Reference: J.J. Degnan, J. Geodynamics, 34, pp. 551-594 (2002).**

# Atmospheric Factor (AF)
## Transmission T=0.2 to 0.8,black = approximation
## $\theta_s$ =0 (red),20(blue),40(brown),60(magenta) deg

# *NGSLR Worst Case Solar Noise vs Receiver FOV*

* The receiver FOV (solid angle) is given by $\Omega_r = \pi\omega^2$ where $\omega$ is the receiver half angle.

* An Atmospheric Factor (AF) = 0.5 is a "worst case" value for target zenith angles less than 70°.

* The NGSLR timer has a 60 nsec deadtime (comparable to an actively-quenched SPAD) and will therefore lose 10% or more of the target data for $\omega > 5$ arcsec.

* With a low deadtime receiver, the MCP/PMT could tolerate $\omega \sim 8.1$ arcsec with no loss of data but the MCP would begin to lose responsivity due to MCP saturation.

* An additional 30 pm etalon filter in the receiver would improve noise tolerance and tube life by a factor of 10. Alternatively, it would allow larger daytime receiver FOV's up to $\pm 25$ arcsec and eliminate the need for transmitter point-ahead in NGSLR. As in GLAS, however, the laser frequency and bandwidth would need to be more tightly controlled.

**Worst Case Noise**

AF = 0.5

5.3   8.1

MCP
SPAD

Noise Count Rate, MHz

Receiver Half Angle, arcsec
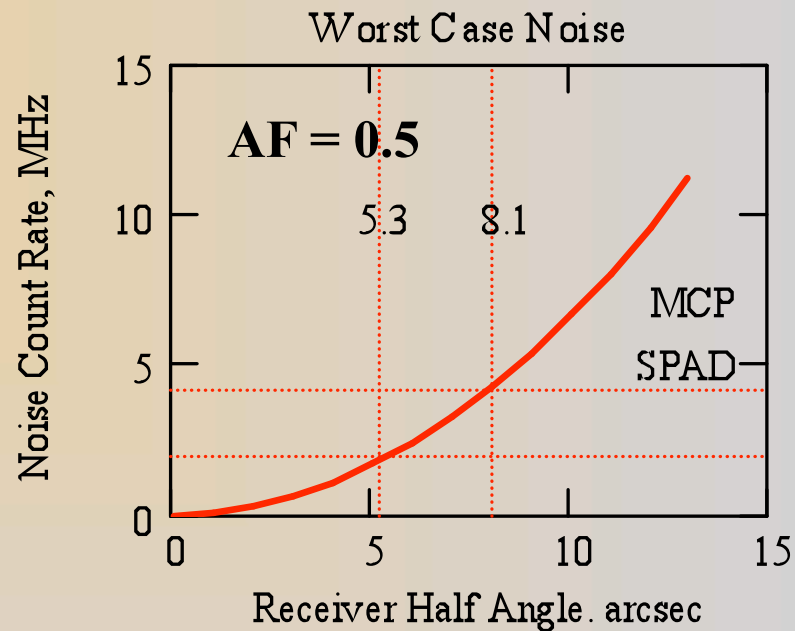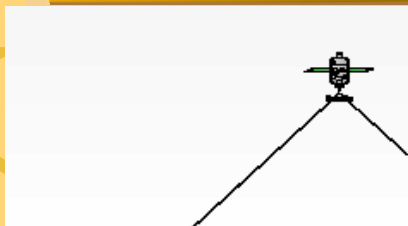
# *What is the Cross Track Channel (CTC) Lidar\*?*

* A secondary high sensitivity, multi-beam, photon-counting lidar proposed by Sigma for the ICESat-II mission to provide cross-track ice slopes and topography.

* A Diffractive Optical Element (DOE) generates 16 parallel beamlets from a <u>single</u>, multikilohertz passively Q-switched laser transmitter (nominally 1 mJ @ 10 KHz = 10W)

* 16 fiber bundles in the GLAS telescope focal plane relay photons reflected from the surface within each beamlet to the detector(s).

* The multistop, single photon sensitive detector and FPGA-based timing receiver record the photon times of flight in each channel with a timer resolution of $\pm 93$ psec ($\pm 1.4$ cm range resolution) and a receiver deadtime of 1.6 nsec.

\* Also referred to as a "pushbroom lidar" in J. Degnan, "A Conceptual Design for a Spaceborne 3D Imaging Lidar", J. e&i Electrotechnik und Informationstechnik (Austria), Vol.4, pp. 99-106, April, 2002.

# CTC Concept
# (Why 16 channels?)



•Assuming 16 beams over 3 km oriented at 45º to flight direction for semiannual yaw rotation, we obtain:

  •16 tracks 141 m apart = 2.1 km actual swath

  •Latitudes above 80º are completely mapped seasonally (>4 times/yr)

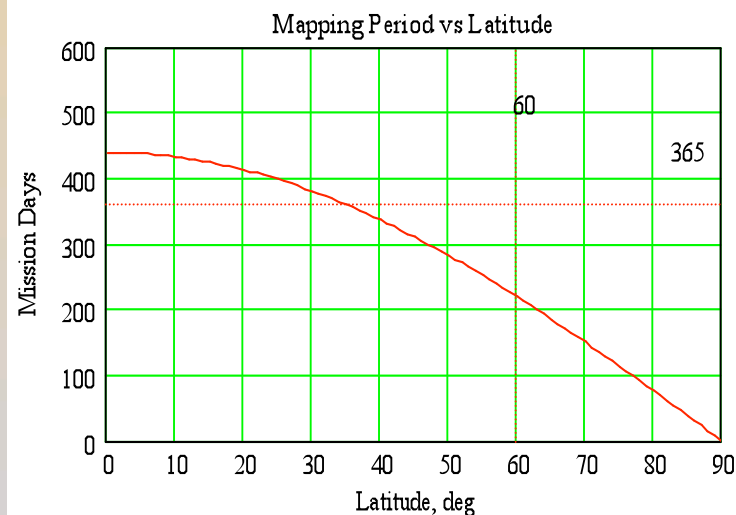  •Latitudes below 35º are completely mapped less than once per year

•A single 10 W laser transmitter is within the state-of-the-art and can support up to 16 channels with 82% surface return rate over ice and snow in a standard clear atmosphere while providing some signal margin for poorer atmospheres.

•Reducing the number of channels marginally increases the return rate while significantly reducing the spatial coverage and resolution.

# *Solar Count Rate* (Altimetry)
## *Combined Surface and Atmosphere*

$$\dot{n} = \left[\frac{\eta_q \eta_r}{h\nu}\right]\left[\frac{N_\lambda^0 (\Delta\lambda)\Omega_r A_r}{\pi}\right]\left[\rho T^{1+\sec\theta_s}\cos\psi + \frac{1 - T^{1+\sec\theta_s}}{4(1+\sec\theta_s)}\right]$$

Spectral & Spatial
Pre-Detection Filters

Surface
Contribution

Atmospheric
Contribution

$A_r$ = Receive telescope area

$T$ = one-way transmittance of the atmosphere at zenith

$\rho$ = surface reflectance

$\theta_s$ = solar zenith angle

$\psi$ = angle between surface normal and the Sun

# *Model Inputs*

* Exoatmospheric Solar Irradiance at 532nm :   $N_0{}^\lambda = 0.2$ W/m$^2$-A$^o$-ster

* Effective GLAS Telescope Area: $A_r = 0.736$m$^2$

* Spectral Bandwidth: $\Delta\lambda = 250$ pm (GLAS coarse filter only) or 25pm (GLAS coarse filter and etalon)

* Receive Solid Angle: $\Omega_r = 2.09\times10^{-9}$ ster per channel (30 m FOV at ground or 50 μrad , 10 m laser footprint, 200 micron fiber in focal plane)

* Worst case solar angle:  $\theta_s = 0$, i.e. Sun's rays parallel to Lidar beam

* Standard Clear Atmosphere Transmission: $T_0 = 0.8$@ 532 nm but varied during modeling.

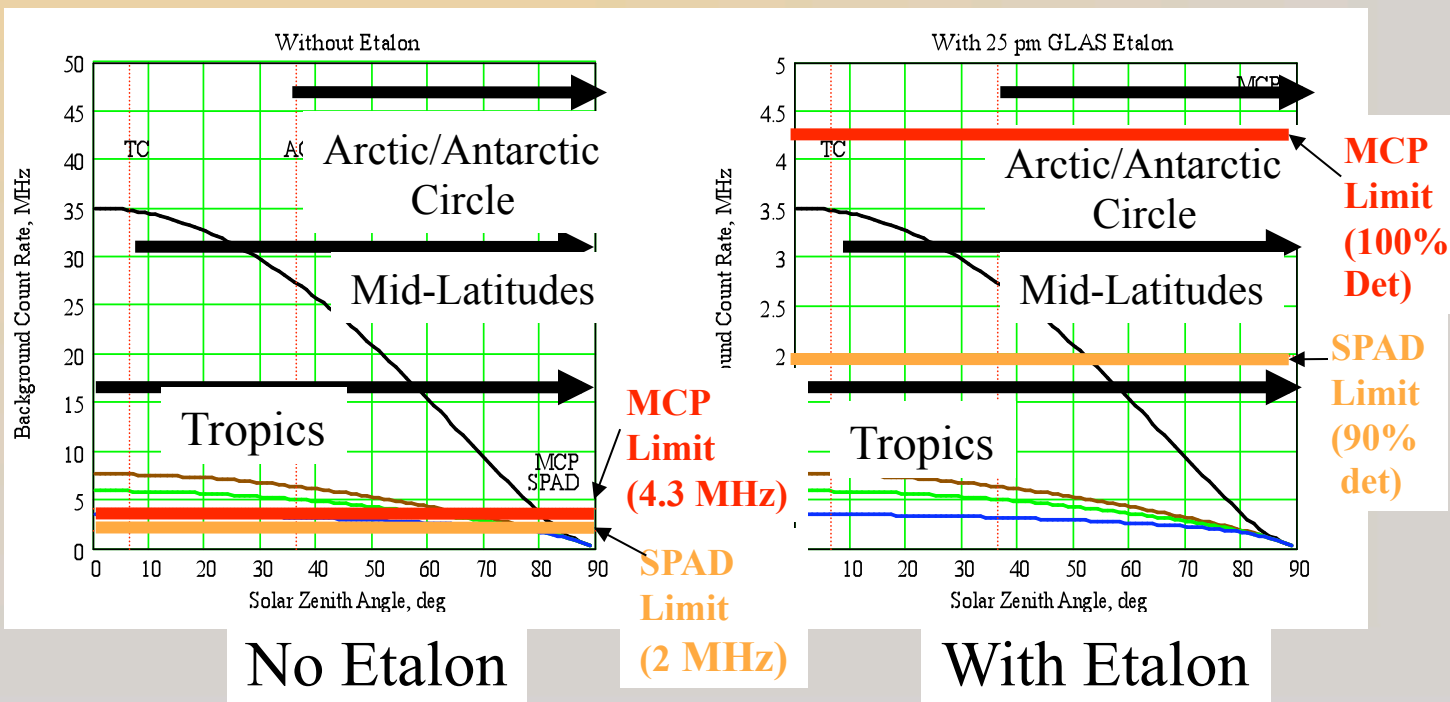* Worst case slope-Sun orientation: $\psi = 0$

# *Solar Noise Background Per Channel*

**(vs receiver spectral bandwidth, solar zenith angle, surface reflectance, and latitude)**
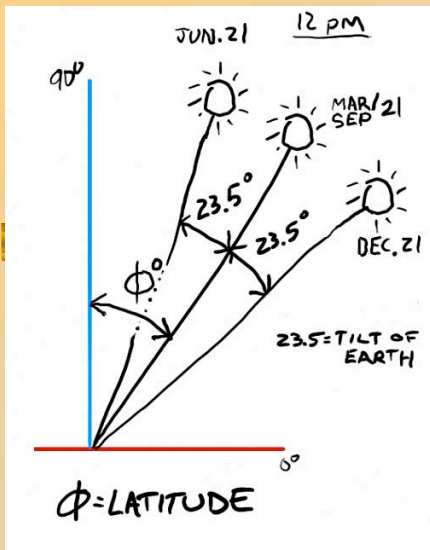
AC= 36.5° = minimum solar angle at 60° lat
TC = 6.5° = minimum solar angle at 30° lat
Black = ice/snow surface
Brown = soil, dry vegetation (15%)
Green = green vegetation (10%)
Blue = water (3%)

No Etalon

With Etalon

# *Summary of Previous Slide*

* Neither detector type (MCP/PMT or SPAD) can function reliably under all daylight conditions without the GLAS 25 pm etalon in the receiver train. Thus, in subsequent calculations, we will assume the GLAS 25 pm filter is part of the receiver optical train.

* With the GLAS etalon, the MCP/PMT can function under maximum background conditions without additional loss of surface counts (beyond normal Poisson detection statistics). However, MCP/PMT lifetime is believed to be limited by the total coulombs/cm$^2$ transferred between the photocathode and anode.

* With the GLAS etalon, a SPAD will lose approximately 10% of the surface counts (over and above Poisson statistics) with a background rate of 2 MHz (assuming a 50 nsec quenching time) and could lose almost 20% under worst case solar background conditions (3.5 MHz). On the positive side, the SPAD does not appear to have any inherent life limitations (beyond electronic malfunctions) based on total exposure or charge transfer..

# *Solar Background over Ice/Snow per Channel vs One-Way Atmospheric Transmission, $T_0$*
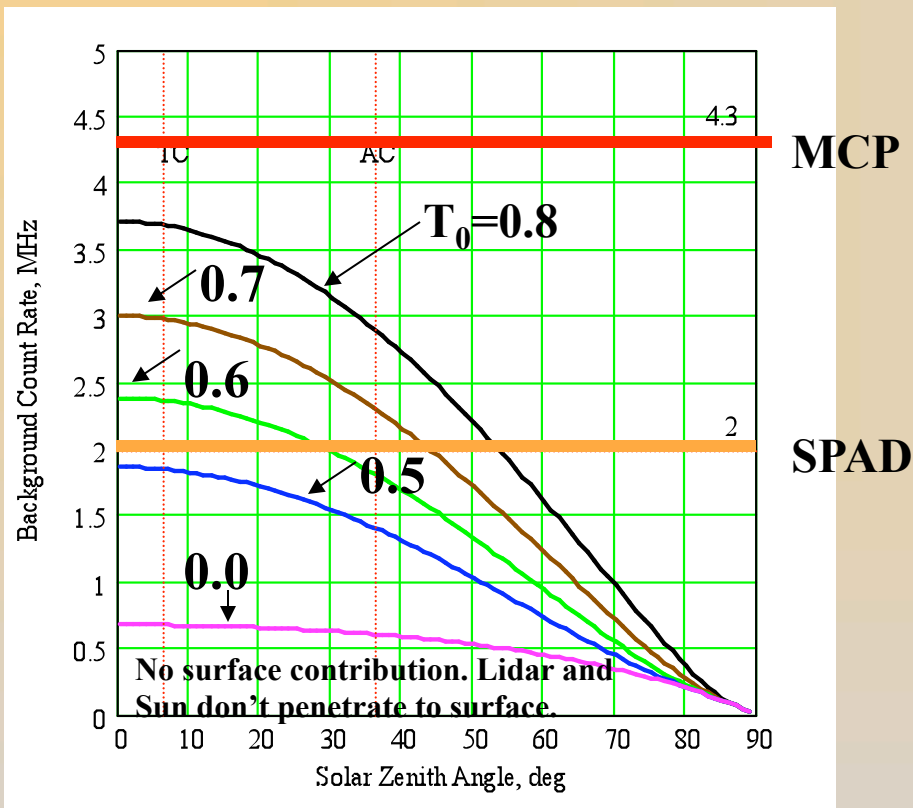


**Assumptions**
- 25 pm etalon in receiver path.
- $\Omega_r$ =Receiver solid angle per channel = $2\times10^{-9}$ ster (30 m)
- Cloud cover included in transmission T and solar photons can backscatter into receiver isotropically.
- Background includes surface contribution except for $T_0$ =0.0 where Sun cannot penetrate.

# *Impact of Temporal (Range) Gating on SLR and Altimetry*

✴ **Temporal Gating Cannot**
- Reduce the solar noise count rate during the gating period
- Improve surface counting statistics for PMTs or SPADs in the presence of high solar noise.
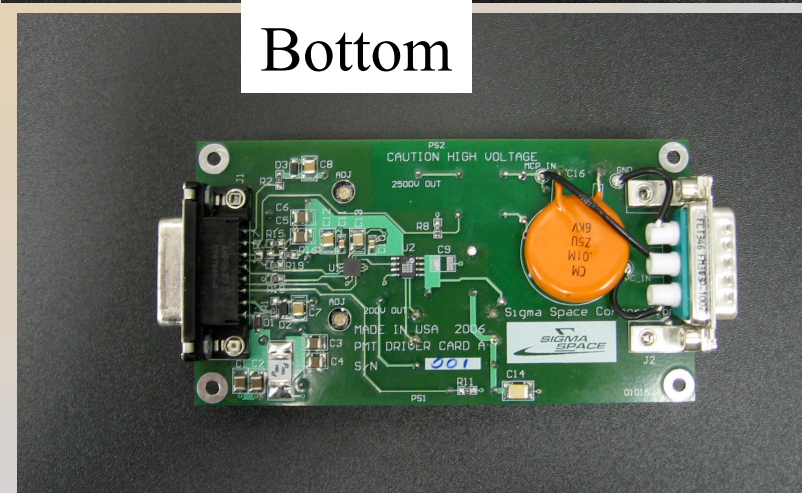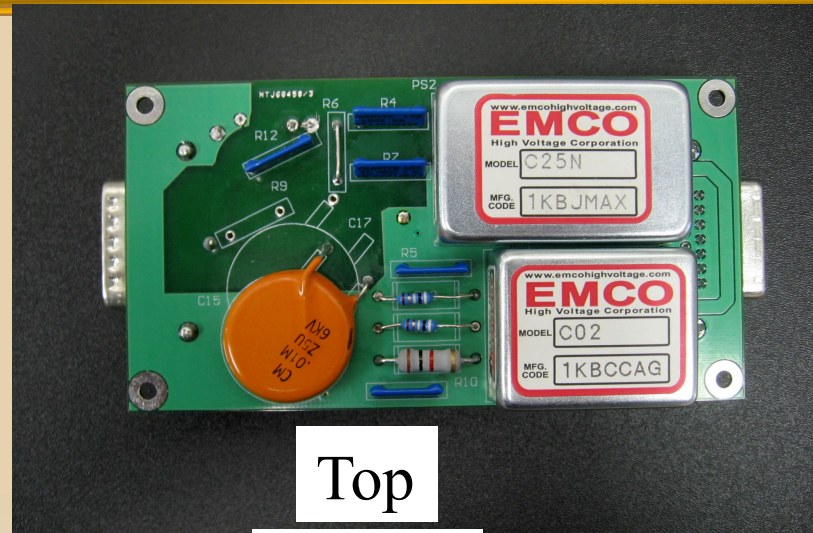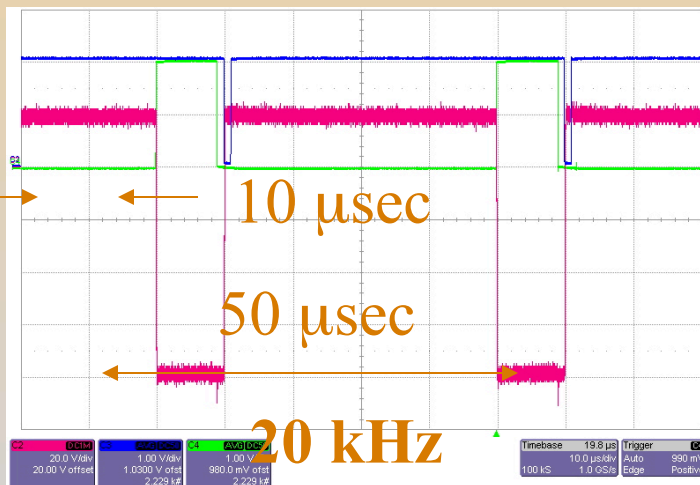
✴ **Temporal Gating Can**
- Substantially reduce the overall solar noise count thereby reducing the total coulomb charge passed by the photocathode to the anode and extending MCP/PMT lifetime by the inverse of the duty cycle.
- Lower the threshold in post-detection filtering by a Correlation Range Receiver and improve signal cell detection probabilities.

# *Sigma 22 kHz PMT Gating Board*

- Provides 200 V gating pulse to turn MCP/PMT on or off
- Tested at rates up to 22 kHz
- Rise/Fall Time: 250 nsec
- Min Gate Width: ~1 μsec

Top

Bottom

10 μsec

50 μsec

**20 kHz**

# *CTC Daytime Noise Counts vs Pre-Detection Filtering Options*

| PC Saturation: 64 GHz<br><br>MCP Saturation: 4.3 MHz for $G = 3 \times 10^5$<br><br>SPAD Limit: 2 MHz (50 nsec) to 1 MHz (100nsec) | Worst Case* Noise Counts per Channel: 38 MHz:<br>*250 pm filter<br>Ungated<br>Sun directly over ice and snow surface<br>Extremely clear atmosphere | Mean Noise Counts per Channel per Interpulse Interval (100 µsec)<br>72% water<br>20% land<br>8% snow/ice<br>50% day/50% night |
|---|---|---|
| Worst case solar noise counts within each laser pulse interval (100 µsec). <u>Typically there is only one surface return per interval</u>. | 3800 (250 pm & ungated)<br>380 (25 pm & ungated)<br>380 (250 pm & 10 µsec gate)<br>38 (25 pm & 10 µsec gate) | 336 (250 pm & ungated)<br>34 (25 pm & ungated)<br>34 (250 pm & 10 µsec gate)<br>4 (25 pm & 10 µsec gate) |

There is roughly an order of magnitude difference between the peak noise count rate and the average rate.

# *Amplitude Filtering*

★ Unlike SPADs which saturate, the MCP/PMT puts out a pulse amplitude proportional to the number of detected photons from the surface. This offers the possibility of raising the post-detection electronic (discriminator) threshold beyond one photon to reduce the number of scattered solar photons detected by the receiver.

★ Unfortunately, surface returns will also be detected with a reduced probability and, due to the nonlinearity of Poisson statistics, weak returns (due to low surface reflectance or poor atmospheric transmission) will suffer the most. However, one can try to partially compensate for the higher threshold by splitting the laser into a smaller number of beams sacrificing spatial coverage.

★ Amplitude filtering does not directly extend MCP/PMT lifetime since it occurs after the electronic charge has already been transferred from cathode to anode. However, post-detection, pre-comparator electronic amplification can be substituted for MCP gain to further extend tube life and avoid MCP saturation.

# *Worst Case Noise Count Rate per Channel vs Detector Threshold*

The Poisson probability of detecting a return containing $n_s$ photoelectrons (pe) when the threshold is set at $n_t$ pe is:

$$P_d\left(n_s, n_t\right) = 1 - e^{-n_s} \sum_{k=0}^{n_t-1} \frac{n_s^k}{k!}$$
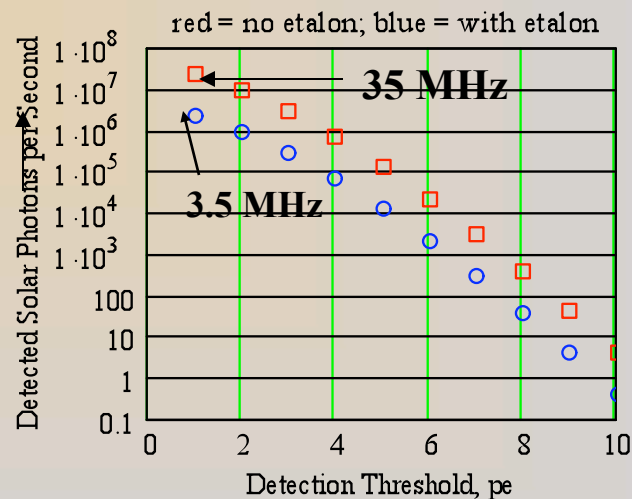
Worst Case (no etalon) = 35 MHz
Worst Case (etalon) = 3.5 MHZ
for 1 pe threshold

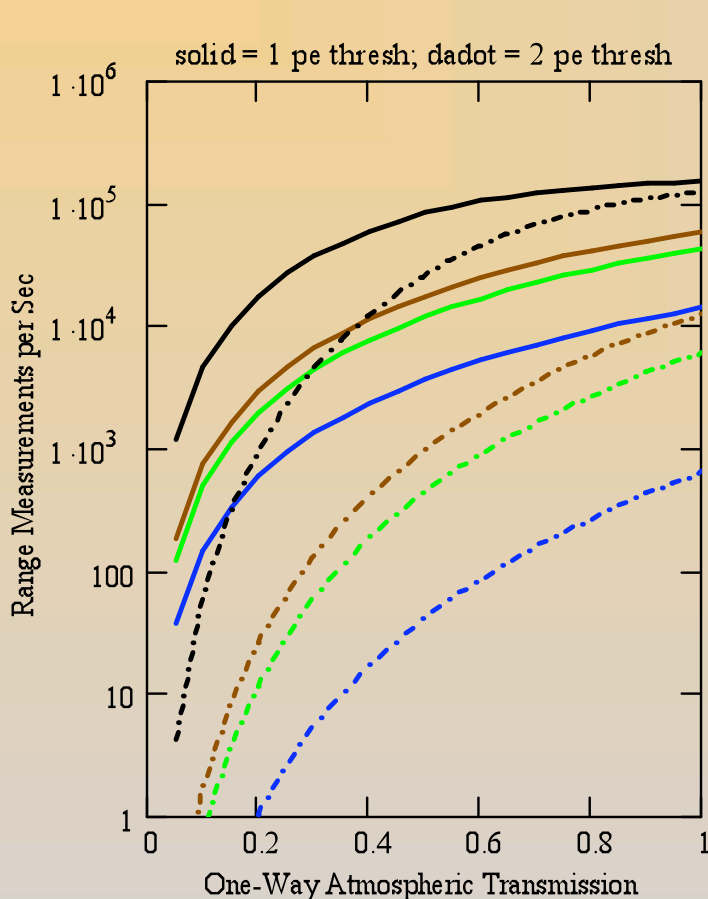Probability of detecting a solar photon as a function of the Threshold K (K =1 to 10)

$\text{PD}_K =$

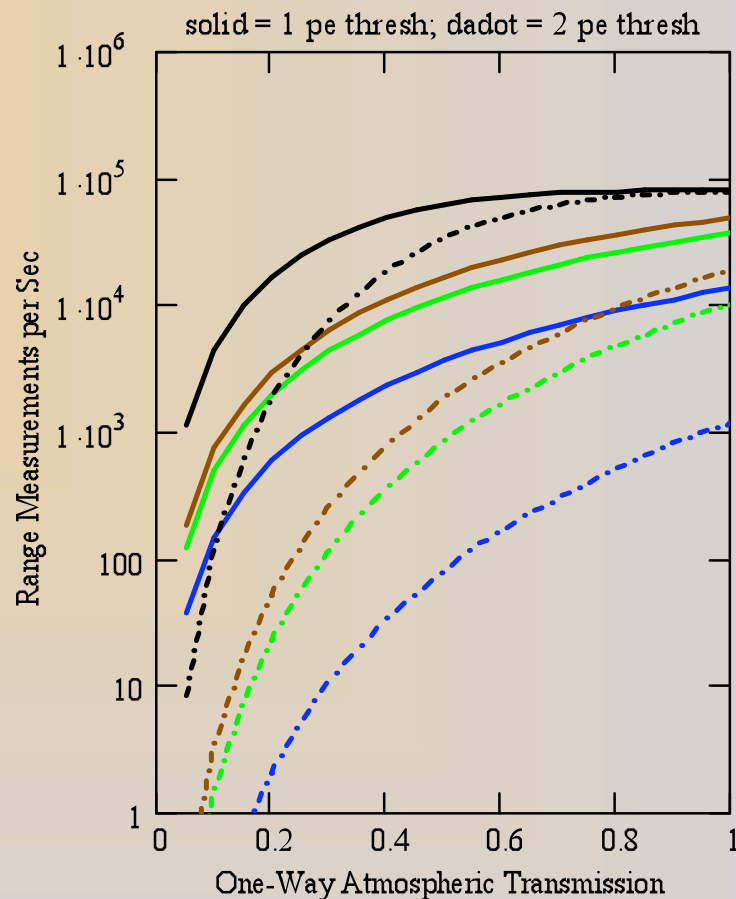| |
|---|
| 0.632 |
| 0.264 |
| 0.08 |
| 0.019 |
| $3.66 \cdot 10^{-3}$ |
| $5.942 \cdot 10^{-4}$ |
| $8.324 \cdot 10^{-5}$ |
| $1.025 \cdot 10^{-5}$ |
| $1.125 \cdot 10^{-6}$ |
| $1.114 \cdot 10^{-7}$ |



red = no etalon; blue = with etalon

# Surface Measurements per Second vs Threshold and Number of Channels

*(black = snow/ice; brown =soil/dry vegetation; green = green vegetation; blue = water)*



16 Channels

8 channels

# *Summary*

* The combined detector/receiver recovery time determines the maximum tolerable noise count rate in photon-counting systems.

* Beating down the noise count rate through aggressive spectral and spatial filtering is the only way to overcome recovery time limitations.

* Temporal filtering (range gating) has no impact on recovery time limitations but can significantly extend MCP/PMT life, reduce data storage and/or transmission requirements, and accelerate the post-detection filtering process.

* Raising the detection threshold above 1 pe (amplitude filtering) results in a significant loss of target data without providing commensurate noise benefits.