Optimal Sub-Exposure Calculator

The optimal sub-exposure calculator is an implementation of the process defined and presented by Dr. Robin Glover. The process seeks to compute a minimal sub-exposure time which considers two sources of noise in an image: camera read noise, and noise from sky brightness (light pollution). The effects of thermal noise on images is not considered in this computation.

The concept in this calculation is to provide a sufficiently long exposure so that the effects of camera read-noise are overwhelmed by the signal coming from the target, but not so long an exposure that effects of sky brightness rise to overwhelming levels in the image.

The implementation of this process does not consider the brightness of the target, nor does it consider other factors which may cause an astrophotographer to choose a another sub-exposure time. These other factors may include: The storage requirements and extended post-processing time for a large number of short exposures. The impacts of external factors that might occur in very long exposures, such as tracking / guiding performance, changes in sky / weather conditions, intrusions from air traffic or passing satelites.

The tool simply provides additional infomation that can be considered by a photographer in selecting an exposure time given the equipment and observing conditions.

The optimal exposure calculation requires:

- Information about the quality of sky at the observation location.
- The focal ratio of the optic.
- A value for the transmission bandwidth of a filter which would be used during imaging.
- Information about the read-noise of the camera, (a map of gain/iso to read-noise values).
- An input for the selected gain / iso value on the camera.
- An input for a tolerance of noise, (allowed noise increase %).

From these inputs the calculator will present graphical presentation of the optimal sub-exposures over the range of available camera gain / ISO values. The user can then make “what if...” adjustments to the inputs of the calculator to immediately see how the optimal sub-exposure time will be effected by the changes, and to see the effects of that exposure time on the noise levels that would be present in stacks of images at various stack (integration) times.

The Sky Quality Measurement (SQM) value, (Noise from Light Pollution)

A Sky Quality Meter provides a measurement of the brightness of the sky in the units of magnitude per square arc-second. The scale will range from around 16 (for a very heavily light polluted sky), to 22.0 (for a sky with no light pollution).

The noise from sky brightness, represents a “variable cost” of taking an image. A short exposure will be less effected by this noise. An exposure that is too long would result in an image which is overwhelmed by light-pollution noise.

A Sky Quality Meter can provide a reading at the time of the imaging session, but an estimated value from sky quality surveys may also be found on the web at sites, (such as https://www.lightpollutionmap.info). But sky brightness is also effected by moonlight scattering in the atmosphere (natural light pollution). The light pollution maps on the web do not account for natural light pollution, (moonlight and the phase of the moon), so there is no effect of moonlight on the SQM value these sites report. So the values from light pollution web sites should probably be considered as a "best case scenario" for a night during a new moon. If a light pollution map value is used for the input value of SQM, but imaging will be performed with a partial moon, then a decrease in the input of the SQM value should be applied in the calculation.

> For example:
>
> At a location where a light pollution map showed an SQM value of 19.63. An SQM reading was made on a night with a waxing crescent, shortly before half-moon, (moon age 5.4, and KStars moon magnitude = -10). The reading at zenith showed a measured SQM value of 18.48.
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> A reading taken on a night with a waxing gibbous, shortly before a full moon, (moon age 12.4, and KStars moon magnitude = -12). The reading at zenith showed a measured SQM value of 15.95.

Optic Focal Ratio

Low optic focal ratios (commonly referred to as "fast" optics), will acquire light (along with noise from light pollution) rapidly. The use of a low focal ratio optic will therefore result in shorter calculated exposure times. Conversely, the use of a high optic focal ratio (a "slow" optic), will result in longer exposure times. A chosen optic will have a specific focal ratio, but changes to optic focal ratio could come from the use of reducers or Barlow lens.

[A deficiency in the calculator is that no consideration is given to the efficiency of the optic. For example two optics of the same focal ratio, a refractor (with no obstruction) and a reflector (with a secondary mirror obstruction) are being treated as equivalent optics in the computations.
One way that a user might compensate for this would be to make an adjustment to the focal ratio input value to compensate for the efficiency of the optic. A refractor is generally considered to have an efficiency of about 94%, a reflector is generally considered to have an efficiency of about 78%.

So the input for the focal ratios might be adjusted as follows:

> Focal Ratio Input for Refractor = Optic Focal Ratio / 0.94
> Focal Ratio Input for Reflector = Optic Focal Ratio / 0.78

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Filter compensation

[Developers: More deficiencies in this area. These deficiencies may not have a significant impact on the calculation, so we may choose to just mention these deficiencies in documentation. But I wanted to raise them just to be thorough.

The presentation by Dr Glover that I watched in 2020 did not provide much detail on how the effects of filters should be considered in the exposure time and noise calculation process.

In researching how other astrophotographers (posting on astonomy forums), have implemented adjustments in calculations they made based on Dr Glover's equations, the effects of filters are only roughly applied; I believe this would be prone to producing some amount of error in the calculation.

Issue #1: All cameras seem to be treated as though they are only sensitive to visible light. The math being employed in the forum posts seems to use a 300 nm bandwidth as the standard for an unfiltered camera, and filter compensation is based on a fraction of this value. But we know that an unfiltered camera is sensitive to some UV and IR light. In reality it may be sensitive to bandwidth of 600 nm or more.

One problem this may create is that the application of a luminance filter; truncating UV and IR bands. The forum posts use 300nm for the bandpass of luminance filters; so with a luminance filter there would be no effect on the noise levels, and no change in the calulated exposure time. From my research, I beleive that mercury lamps emit a considerable amount of UV light and I would think that a truely unfiltered camera would see this as noise.

Issue #2: The compensation for the use of some filters seems to assume an even distribution of light pollution across the spectrum.

On the forum posts the compensation for a R, G, or B filters seem to all be treated as a 100 nm bandwidth. So noise from light pollution with an R, G, or B filter is adjusting the light pollution to 1/3 that of an unfiltered value. This seems erroneous to me, mainly because pollution from artificial light is not distributed evenly across the spectrum. There are very specific emission lines from the common sources of atrifical light pollution, sodium and mercury light sources. For example I would think that a blue filter would be passing much more artificial light pollution from a mercury lamp than would a green or red filter.

Issue #3: No adjustment seems be getting applied for the fact that a filter may only be transmitting at 95% efficiency within the bands that it passes. For example, if an R, G, or B filter actually is passing band width of 100nm, but it is only 95% efficient in that range, then the filter compensation value for the calculation should probably 95, not 100.
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Camera gain / ISO selection and the resulting camera read-noise

[At this time, only CMOS cameras are supported in the calculator. CCD cameras have a fixed read-noise, and do not have a gain adjustment like CMOS cameras. But CCD cameras tend to be more efficient in conversion of light, so the exposure times with CCD cameras should be lower than for CMOS cameras. Further research is required to determine how to apply a sensor efficiency factor in the calculation for CCD cameras.]

Read-noise is incurred at the instant that the exposure has completed, as the voltages within the pixels of the imaging sensor are being read and converted to numeric values through an electronic circuit known as an analog to digital converter (ADC).

For a given gain or ISO setting on a camera, there will be a pre-determined read-noise value. Details of this gain to read-noise relationship may be published in the technical documentation of some cameras, but the calculator tool will rely upon a data file for the camera which include transcribed data from the camera technical documentation in order to determine the a read-noise value, and produce a correct calculation for an exposure.

For this initial implementation of this sub-exposure calculator, the first execution of the tool will trigger the creation of a folder for the storage of camera data files, and several camera files will be written into the folder. (See section on camera file naming below). For the long-term implemnatation of this calculator the camera read-noise data files will be user maintained and will be downloadable.

The read-noise in an image can be thought of as a “fixed cost” of taking an image. A long exposure does not incur a greater amount of read noise than a short exposure.

When the camera is producing a high read-noise, the calculation for exposure time will be increased. This is because more exposure time will be needed to overwhelm the read-noise with the desired data from the target.

On a CMOS camera, a read-noise level will normally vary with a change in the selected gain or ISO value on the camera. The selection of low gain / ISO values will typically result in high read-noise values, and therefore higher exposure times. Conversely a high gain / ISO value will typically result in low read-noise values, and therefore lower exposure times. However, the selection of a high gain/ISO will reduce the dynamic range in the image, and the selection of a low gain/ISO will result in higher dynamic levels in the image. So the photographer must weigh the benefits and costs in choosing a gain / ISO setting.

Some cameras may show a smooth progression curve in the read-noise over the range of gain values, other cameras may have very pronounced steps (and other anomalies) in their read-noise. These pronounced steps are usually the result of electronic mode switching within the camera. A few cameras have an option to select among different read-noise operational modes, and these operational modes would each have a unique gain to read-noise “map”.

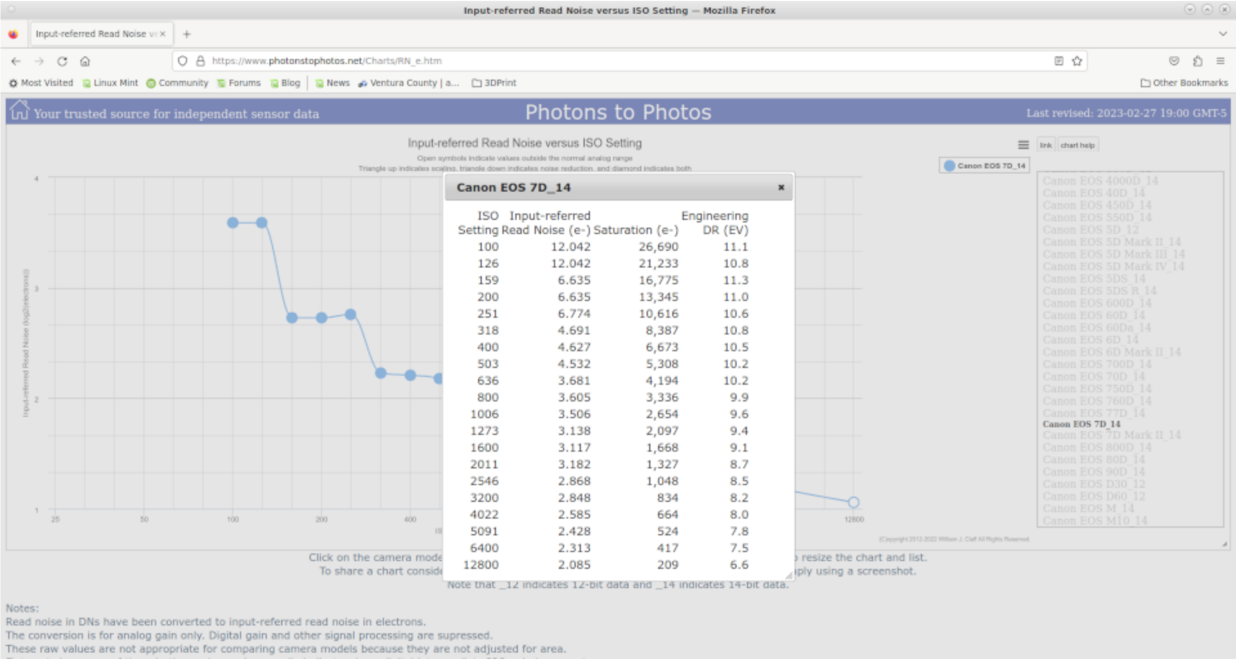
Hint: For a selected camera which has a pronounced step in its read-noise, a photographer may wish to select a gain which is at the bottom of that step. This may provide a reduced read noise, and shorter exposure without a significant loss in dynamic range when compared to an image shot at a gain selection that is at the top of that step. But caution is needed when selecting a gain near a “step” on the graph. Some posts on forums indicate that the read-noise data provided by manufacturer documentation may not be exact. The actual “switch” in read-noise may be at a slightly higher or lower gain value. So it might be wise leave a slight gap between the graphically shown step, and the selected gain value in the calculator.

[Developers: To ease the difficulty in the creation of new camera files please see the buildSensorDataFile method in fileutilitysensordata.cpp. The sample camera data files are built with this method. A copy, paste and edit of an existing camera data definition, might be quickest way to create a new camera data file.]

If you wish to add a DSLR, there is a great site for ISO to read-noise data :
https://www.photonstophotos.net/Charts/RN_e.htm

On this website, after a camera is selected, a graph will appear, but by clicking the box with the camera name table will appear with data that can be harvested for the gain to read-noise data map.

Just be aware that for a DSLR you need to set the gain selection type enum to GAIN_SELECTION_TYPE_ISO_DISCRETE and the gainSelection vector needs to list the actual selectable ISO values that the camera supports).



Canon EOS 7D_14

ISO Setting	Input-referred Read Noise (e-)	Saturation (e-)	Engineering DR (EV)
100	12.042	26,690	11.1
126	12.042	21,233	10.8
159	6.635	16,775	11.3
200	6.635	13,345	11.0
251	6.774	10,616	10.6
318	4.691	8,387	10.8
400	4.627	6,673	10.5
503	4.532	5,308	10.2
636	3.681	4,194	10.2
800	3.605	3,336	9.9
1006	3.506	2,654	9.6
1273	3.138	2,097	9.4
1600	3.117	1,668	9.1
2011	3.182	1,327	8.7
2546	2.868	1,048	8.5
3200	2.848	834	8.2
4022	2.585	664	8.0
5091	2.428	524	7.8
6400	2.313	417	7.5
12800	2.085	209	6.6

Click on the camera mode … resize the chart and list.
To share a chart consid … ply using a screenshot.
Note that _12 indicates 12-bit data and _14 indicates 14-bit data.

Notes:
Read noise in DNs have been converted to input-referred read noise in electrons.
The conversion is for analog gain only. Digital gain and other signal processing are supressed.
These raw values are not appropriate for comparing camera models because they are not adjusted for area.

[Camera File Names:

When started, the calculator will attempt to automatically select the appropriate camera from the QCombo. The active camera device name is used for this selection. The QCombo is populated by reading the file names in the camera folder. (But the calculator code will transform between spaces in the device name with underscores in the file name).

So a camera should be named as it appears with it's device name in ekos/indi. The name of the file for that camera would have have underscores for spaces, and an extension of ".xml".
Example: Camera device name "ZWO CCD ASI2600MM Pro", would be stored in the user local share folder as /kstars/exposure_calculator/ZWO_CCD_ASI2600MM_Pro.xml.

Unfortunately, since I only own three cameras, I had no way to confirm how most of the example cameras I created appear in ekos device name, I made some guesses, but many camera file names may need to be corrected.
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Noise Increase %

The Noise Increase %, (Dr Glover refers to this as "Allowable Noise Increase %"), is part of the calculation of a coefficient that governs the proportion of read-noise to light pollution noise in the calculation of the optimal sub-exposure (Dr Glover refers to this part of the calculation as the "C Factor"). When looking at the results of an exposure calculation, the noise increase % would be seen in the relationship of the shot noise to total noise; the allowed noise increase = (total noise – shot noise) / shot noise.

In practice; a high value for the "Noise Increase" will produce a lower exposure time than would a low "Noise Increase" value. Dr Glover recommended 5% as a reasonable value for the Allowable Noise Increase %, as there are diminishing returns for increasing the exposure time to provide a reduction of noise in a stack. But there may be some exceptions that provide good reasons to deviate from this 5% value.

The calculator allows for adjusment of this value; the change will alter the balance of read-noise to light pollution noise. Increasing this allowable value will shift the balance to more read-noise and less noise from slight pollution; and a shorter exposure time will be computed. Decreasing allowable noise will shift the balance to less read-noise and more noise from light pollution; and a longer exposure time will be computed. The value cannot be set to 0, as this would cause a computation of an infinite exposure time. But a lower value may slightly improve the noise ratio in a stack.

At an observation site with low sky quality, using a fast optic, and moderate filtering, the calculation may produce a sub-exposure time that is in the single digits (or even low single digits). In such a case, lowering the input value for the "Noise Increase", will raise the exposure time, and in doing so, fewer exposures will be needed for a given stack time. The relationship of shot noise to total noise will change, and the signal to noise ratio in a stack of images should improve slightly.

For example: At SQM 18.5, a Focal Ratio f/4, with a QHY 268m at gain 50 (in photographic mode), and a luminance filter: the calculation with allowable noise increase at 5% produced an exposure time of just 2.4 seconds. But reducing the allowable noise increase to 0.25% raised the exposure time to 50 seconds. The ratio of noise in stacked improved by a very small fraction. Unfortunately, these images will be relativly high noise due to the sky quality being rather poor.

Conversely, at a location with a good sky quality, with a slower optic, and narrow-band filtering, the calculation may produce a sub-exposure time that is much longer than desired.

For example: At SQM 20, Focal Ratio f/6, with a QHY 268m at gain 50, and a 5 nm filter. With noise increase at 5%, the calculation will produce a exposure time of 1476 seconds, (over 24.5 minutes)! This is likely much longer than the photographer would prefer given concerns for guiding, etc. By raising the allowable noise to 25% the exposure time drops to 269 seconds. But in this case the read-noise is very large relative to the noise from light pollution, and the stacks will show a much worse noise ratio than could be achived at the optimal 24.5 minute exposure. Fortunately, the stacks with exposures of 269 seconds will still be relatively low noise due to the lower light pollution.

In cases of very good sky quality, a fast optic, and narrow-band filtering, the calculated optimal sub-exposure times will be extremely long, and raising the input value for the "Noise Increase" may still not lower the sub-exposure time to a reasonable length. With such equipment and in such good viewing conditions, the calculator may not provide a great deal of benefit.

Diminishing returns of quality from stacking

A photographer will need to make decisions with regard to the investment of time in a stacked exposure.

Taking an example case:
SQM 19, F/5, Filter RGB (100), Camera ASI 2600MM, Gain 0, Noise Increase 5%

This resulted in an optimal exposure time of 32 seconds. But as you can see in the data, the ratio (quality) increases in relation to the square root of the hours of stack time (or the square root of the count of exposures). This results in a curve where the image quality improvement for increasing stack time is diminishing. To put in another way, adding 1 hour of exposure time from 3 hours to 4 hours improves the quality by 15%. But adding 1 hour of exposure time from 23 hours to 24 hours only improves the quality by 2%.

Charting this we see that the Stack Noise and the Ratio (quality), are curves which are flattening as the hours of stack time are increased.

Planned Hours	Exposure Count	Stack Time (Seconds)	Stack Noise	Ratio
1	112	3608	113.8	31.7
2	224	7217	161.0	44.8
3	336	10826	197.2	54.9
4	447	14403	227.4	63.3
5	559	18012	254.3	70.8
6	671	21621	278.7	77.6
7	783	25229	301.0	83.8
8	894	28806	321.6	89.6
9	1006	32415	341.2	95.0
10	1118	36024	359.7	100.2
...	...	...	...	...
20	2235	72016	508.6	141.6
21	2347	75625	521.1	145.1
22	2458	79201	533.3	148.5
23	2570	82810	545.3	151.9
24	2682	86419	557.1	155.1
25	2794	90028	568.6	158.3