P1.7

QUANTIZATION NOISE FOR GOES-R ABI BANDS

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1. Introduction

This paper deals with the subject of noise introduced by the quantization of a range of measurements into a limited number of counts. In the case of GOES-R both cold cloud-top and fire hot-spot temperatures are desired from the ABI shortwave infrared band, as the prime example. When a large range of measurement is desired the digital scale needs to be divided sufficiently finely so that the difference between adjacent values on the scale, the quantization noise, is not a significant limiting factor. It will be shown that a 14-bit scale is the minimum number of bits needed to meet the target delta radiance per count step (based on the requirements of specified noise and desired maximum scene temperature of 400 K). This scale results in a quantization noise per count step of 4.2 K @ 200 K. [Current-GOES quantization noise is 9.5 K @ 200 K (utilizing a 10-bit scale and a maximum scene temperature of 335 K).]

Certain specifications are set for the GOES-R Advanced Baseline Imager (ABI) (Schmit, 2004; ABI-Related Links 2004). Two of those specifications are allowable instrument noise and the instrument maximum scene temperature for each band. As a result of those specs, other characteristics of the ABI data streams, either the raw downlink or the uplink (GOES Re-Broadcast or GRB) can be determined. One of those characteristics is the bit-depth or number of bits used to represent the radiances measured by the ABI. This in turn determines the quantization of the measured radiances and the quantization "step" or the minimum change that can be described in the digitized scale. The desire is that this quantization step per count be much less than the actual radiance noise in order to not put an artificial limit on the radiance noise of the ABI. Calculations are made and results will be presented on the minimum number of bits needed to capture the desired range of temperatures as well as exceed the noise spec for each ABI band. Of course it may turn out that the maximum number of bits needed for any band will be used for all bands. For example, the current-GOES instruments have 10-bit for the Imager and 13-bit for the Sounder.

Among the ABI bands, the 3.9 µm band is of primary interest because of its greater sensitivity to warm temperatures and the desire to capture very hot scene temperatures for detection and characterization of hot spots (e.g., forest and range fires). Thus this shortwave infrared band has a specified instrument maximum scene temperature of 400 K, much greater than the specified temperatures for the other ABI bands. Due to the finer field-of-view size of the ABI (compared to the current GOES imager), this hotter saturation temperature is needed. Of course this same shortwave band, while used for cloud characterization on the cold temperature end, suffers the most from increasing noise (in temperature units) at low scene temperatures, as a result of the basic physics of the Planck equation for shorter wavelengths. Temperature noise in this band is much greater at low temperatures than that for the other ABI bands and can be an undesirable feature of the increased instrument maximum scene temperature.

2. Why is there a concern about bit depth?

When viewing cold scenes, shortwave band imagery suffers from large changes in temperature for small changes in measured radiance. This results in a noisy appearance of the imagery at cold cloud-top temperatures. Figure 1 is a comparison of shortwave (3.9 µm) and longwave (11.0 µm) MODIS images of a thunderstorm at 1 km spatial resolution. Cold and overshooting cloud tops are masked by the larger quantization error at the cold end of the radiance-to-count scale in the shortwave image compared to a longwave image of the same scene.

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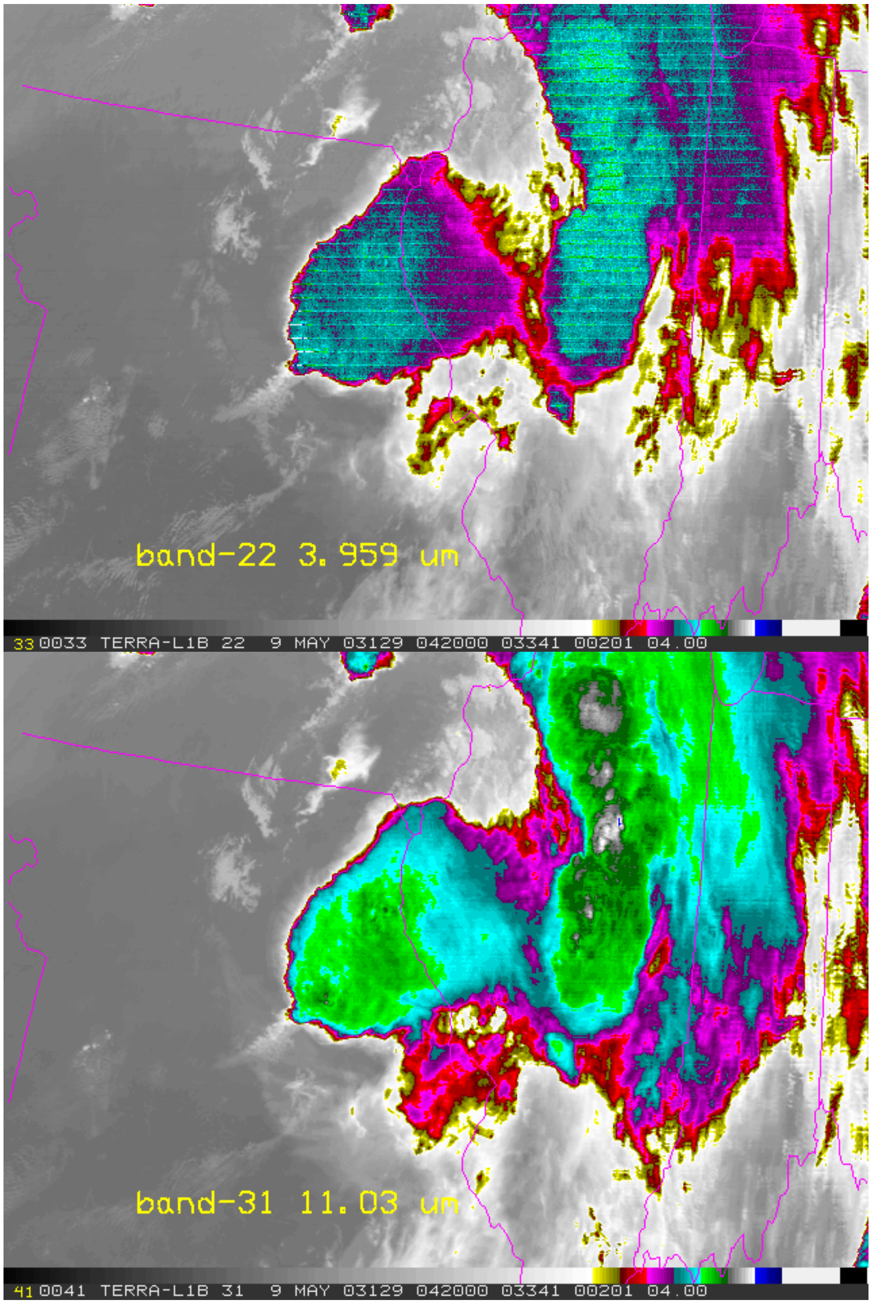

Figure 1: Shortwave (3.9 µm) image on top, and longwave (11.0 µm) on bottom. Both are MODIS images of a thunderstorm at 1 km spatial resolution. Cold and overshooting cloud tops are masked by the larger quantization error at the cold end of the radiance-to-count scale in the shortwave image compared to a longwave image of the same scene.

3. Bit-Depth Methodology

With the focus on the GOES-R ABI shortwave band (3.9 µm), Figure 2 gives a graphical representation of the process of determining the bit-depth needed to meet the requirements of both the maximum and minimum temperatures that need to be measured, as well as the desired target delta radiance for measurements. The delta radiance needs to be precise enough to not allow quantization errors, or a difference that is too large between adjacent values, that would dominate a smooth scaling of the measurements.

The process involves expanding the range of needed temperatures by a fixed temperature increment of 10 K (on the hot end) and extending the temperature down to 0 K (on the cold end). This assumes that space-view measurements near 4 K are desired for calibration purposes. The temperature range is further expanded on each end by a multiple of 5 times the desired Noise Equivalent Delta Temperature (NEdN), to be sure that noise does not interfere with the measurements on either end of the scale. The scale is then divided by the target delta radiance, which is related to a fixed factor times the NEdN, that factor being 1 over 2.5 in this case, again to be sure that the quantization into counts does not limit the measurements in any way.

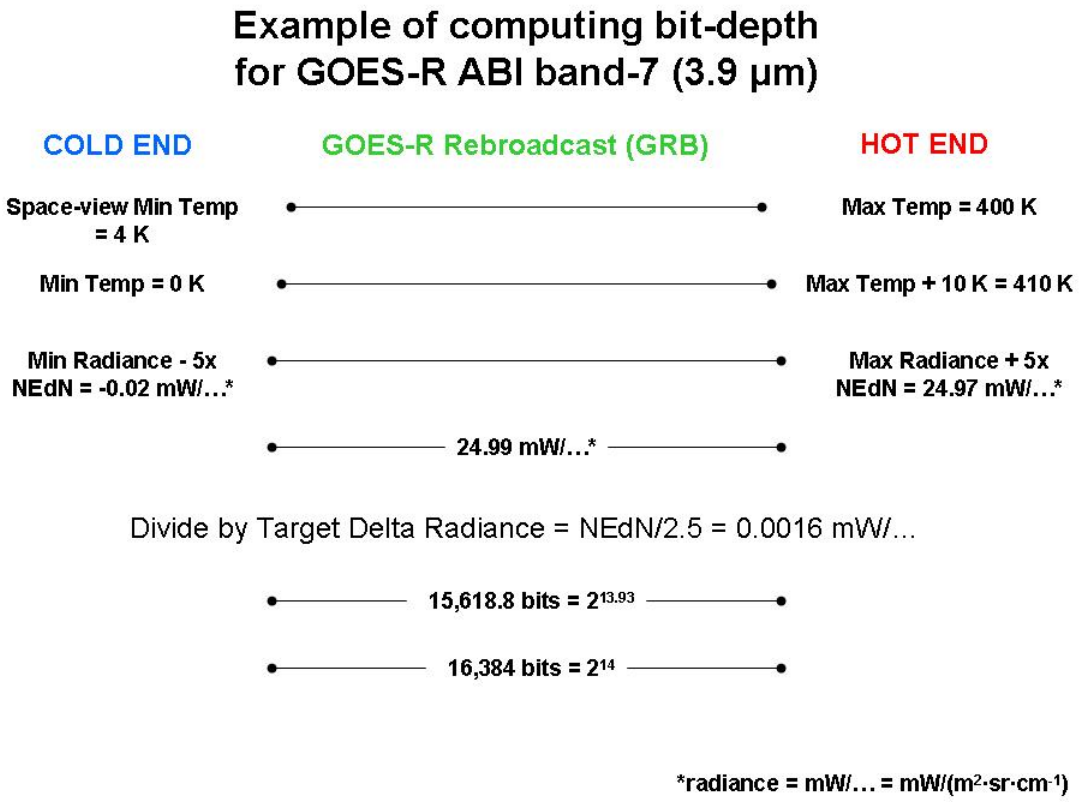

Figure 2: Example of computing bit-depth needed for GOES-R ABI band-7 (3.9 µm)

The process outlined graphically in Figure 2 has been applied to GOES-R ABI infrared bands 7-16, with results in Tables 1a, b, and c. The result is the required bit depth for each band, and the delta radiance count per count step that results from that bit depth.

Table 1a: Relating ABI Specifications of Noise and Instrument Max Scene Temperature to Maximum Radiance [Radiance units: mW/… = mW/($m^2 \cdot sr \cdot cm^{-1}$)]

ABI Band	Central Wavelength (µm)	Spec NEdN[1] (mW/…)	Instrument Maximum Scene Temperature[2] (K)	Maximum Scene Temperature (K) for Scaling[3]	Max Scene Radiance plus 5x noise (mW/…) for Scaling[4]
7	3.9	0.004	400	410	25.0
8	6.185	0.05	300	310	28.1
9	6.95	0.09	300	310	45.3
10	7.34	0.1	320	330	80.2
11	8.5	0.13	330	340	135.4
12	9.61	0.16	300	310	109.2
13	10.35	0.17	330	340	184.4
14	11.2	0.17	330	340	200.0
15	12.3	0.17	330	340	213.2
16	13.3	0.53	305	315	171.7

[1] From Radiometric Precision Table of *ABI Performance and Operational Requirements Document (PORD), 2004*.

[2] From Dynamic Range Table of *ABI Performance and Operational Requirements Document (PORD), 2004*.

[3] Instrument Maximum Scene Temperature plus 10 K, based on *GVAR IR Scale Factor Coefficient memo, 1991*.

[4] Five times multiplication factor for the Spec Noise, based on *GVAR IR Scale Factor Coefficient memo, 1991*.

Table 1b: Relating ABI Specifications of Noise and Instrument Max Scene Temperature to Minimum Radiance [Radiance units: mW/… = mW/($m^2 \cdot sr \cdot cm^{-1}$)]

ABI Band	Central Wavelength (µm)	Spec NEdN (mW/…)[1]	Instrument Minimum Scene Temperature (K)[2]	Minimum Scene Temperature (K) for Scaling[5]	Min Scene Radiance minus 5x noise (mW/…) for Scaling[4]
7	3.9	0.004	4	0	-0.020
8	6.185	0.05	4	0	-0.25
9	6.95	0.09	4	0	-0.45
10	7.34	0.1	4	0	-0.5
11	8.5	0.13	4	0	-0.65
12	9.61	0.16	4	0	-0.80
13	10.35	0.17	4	0	-0.85
14	11.2	0.17	4	0	-0.85
15	12.3	0.17	4	0	-0.85
16	13.3	0.53	4	0	-2.65

[5] Radiance from space assumed to be zero for all bands, based on *GVAR IR Scale Factor Coefficient memo, 1991*.

Table 1c: Relating ABI Specifications to Required Bit Depth
[Radiance units: mW/… = mW/(m^2·sr·cm^{-1})]

ABI Band	Central Wavelength (µm)	Spec NEdN (mW/…)[1]	Target Delta Radiance per Count Step: NEdN/2.5[6] (mW/…)	Radiance Range (mW/…) for Scaling[7]	Minimum Number of Bits Required[8]	Resulting Delta Radiance per Count Step[9] (mW/…)
7	3.9	0.004	0.0016	25.0	14	0.0015
8	6.185	0.05	0.020	28.4	11	0.014
9	6.95	0.09	0.036	45.8	11	0.022
10	7.34	0.1	0.040	80.7	11	0.039
11	8.5	0.13	0.052	136.1	12	0.033
12	9.61	0.16	0.064	110.0	11	0.053
13	10.35	0.17	0.068	185.2	12	0.045
14	11.2	0.17	0.068	200.4	12	0.049
15	12.3	0.17	0.068	214.0	12	0.052
16	13.3	0.53	0.21	174.3	10	0.17

[6] Factor of 2.5 based on e-mail correspondence with Mike Weinreb, 2004.
[7] Radiance Range between Max and Min Scene Radiances with noise.
[8] Radiance Range divided by Target Delta Radiance and rounded up to next whole bit.
[9] Delta Radiance based on rounded whole bits.

4. Quantization Noise for ABI Band-7

Our study will now focus on the quantization noise as a function the scene temperature for ABI band-7 (3.9 µm). The bit-depth needed for any ABI band can then be translated into a quantization noise. The process takes into account the fact that the temperature difference between counts increases significantly for colder scene temperatures, a result of the basic physics of the Planck function. Figure 3 shows for the shortwave infrared band that the delta temperature (on the y-axis) per fixed delta radiance (on the x-axis) increases sharply as the scene temperature decreases.

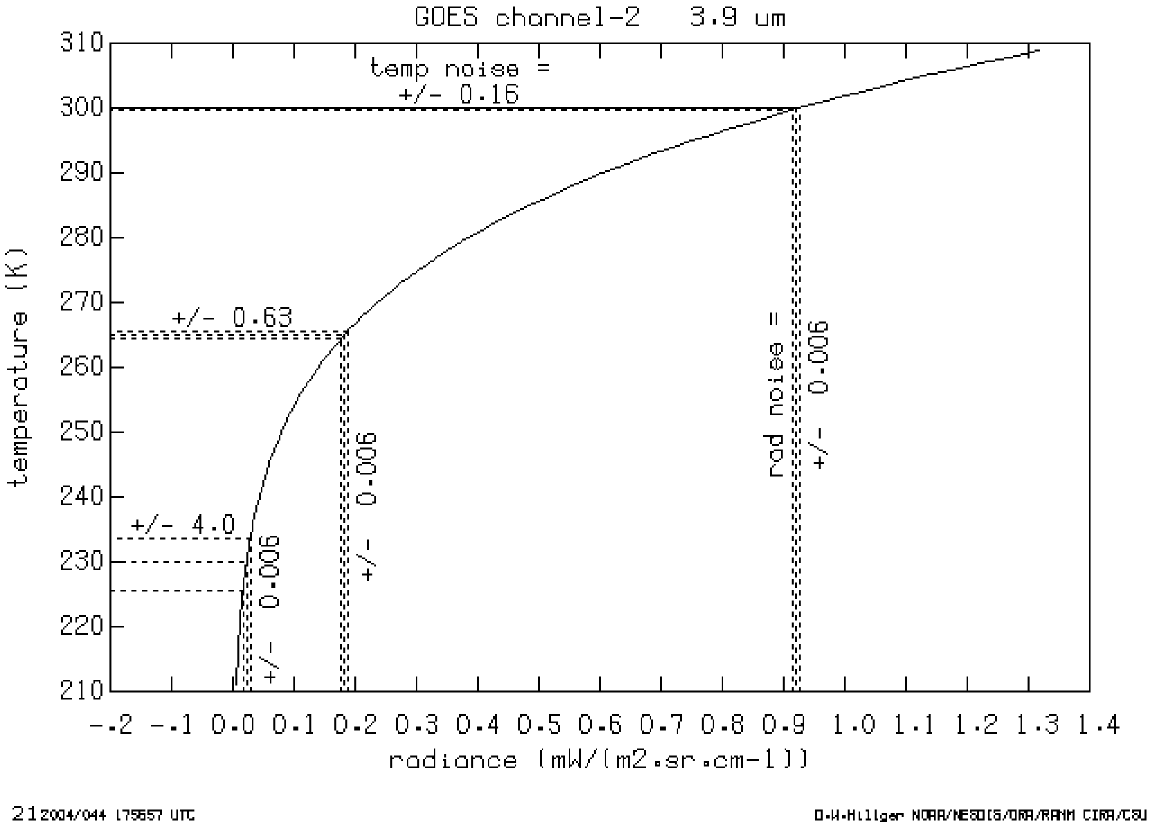

Figure 3: The Planck function for the GOES shortwave infrared window band (3.9 µm) showing how the same delta radiance translates into vastly different delta temperatures as a function of the scene temperature, with much larger delta temperatures for cold cloud tops viewed by this band.

The process shown graphically in Figure 3 has been applied to the GOES-R ABI shortwave infrared band (3.9 µm) for both cold cloud tops (200 K) and warm scenes (300 K), with results in Table 2a and b respectively. In each table the quantization noise for each band is given as a function of both the maximum desired scene temperature and the number of bits allowed by various scales. The results in Table 2a are the crucial ones, as the quantization noise on the warm end (Table 2b) is insignificant except for small bit depths (10-bits) and very warm scene temperatures (400 K).

Table 2a: Relating Instrument Maximum Scene Temperature and Number of Bits to Quantization Noise for Cold Cloud Tops (using a linear radiance-to-count conversion)

Quantization Noise (K) @ 200 K ABI band-7 (3.9 µm)		Number of Bits			
		10-bit (0-1023)	12-bit (0-4095)	14-bit (0-16,383)	16-bit (0-65,535)
Maximum Scene Temperature (K)	350	28.4	4.9	1.2	0.30
	375	∞	9.9	2.3	0.58
	400	∞	21.2	4.2	1.0

Notes:
- Current-GOES quantization noise is 9.5 K @ 200 K (utilizing a 10-bit scale and a maximum scene temperature of 335 K).
- ABI noise spec (0.1 K @ 300 K and 1.4 K @ 240 K) is equivalent to a noise of 32.1 K @ 201 K.

Table 2b: Relating Instrument Maximum Scene Temperature and Number of Bits to Quantization Noise for Warm Scenes (using a linear radiance-to-count conversion)

Quantization Noise (K) @ 300 K ABI band-7 (3.9 µm)		Number of Bits			
		10-bit (0-1023)	12-bit (0-4095)	14-bit (0-16,383)	16-bit (0-65,535)
Maximum Scene Temperature (K)	350	0.093	0.023	0.0058	0.0015
	375	0.18	0.045	0.011	0.0028
	400	0.32	0.081	0.020	0.0051

Notes:
- Current-GOES quantization noise is 0.060 K @ 300 K (utilizing a 10-bit scale and a maximum scene temperature of 335 K).
- ABI noise spec (0.1 K @ 300 K)

Based on the requirements of a desired maximum scene temperature of 400 K, and a 14-bit scale as the minimum number of bits needed to meet the target delta radiance per count step (from Table 1c), the resulting quantization noise per count step in Table 2a is 4.2 K @ 200 K. [Current-GOES quantization noise is 9.5 K @ 200 K (utilizing a 10-bit scale and a maximum scene temperature of 335 K).] Figure 3 shows graphically the results for this combination of 400 K instrument maximum scene temperature (410 K maximum scene temperature for scaling) and 14-bits of depth. Vertical dashed lines are imposed temperature limits. The horizontal dashed line is standard 1-byte count-to-temperature Look-Up-Table (LUT) currently used for display of GOES imagery (Hillger 1999). This LUT has 0.5 K precision above 242 K (-31°C) and 1 K precision below that temperature. The temperature precision for this band increases rapidly for low temperatures and is greater than the desired LUT precision for temperatures below about 220 K (-53°C).

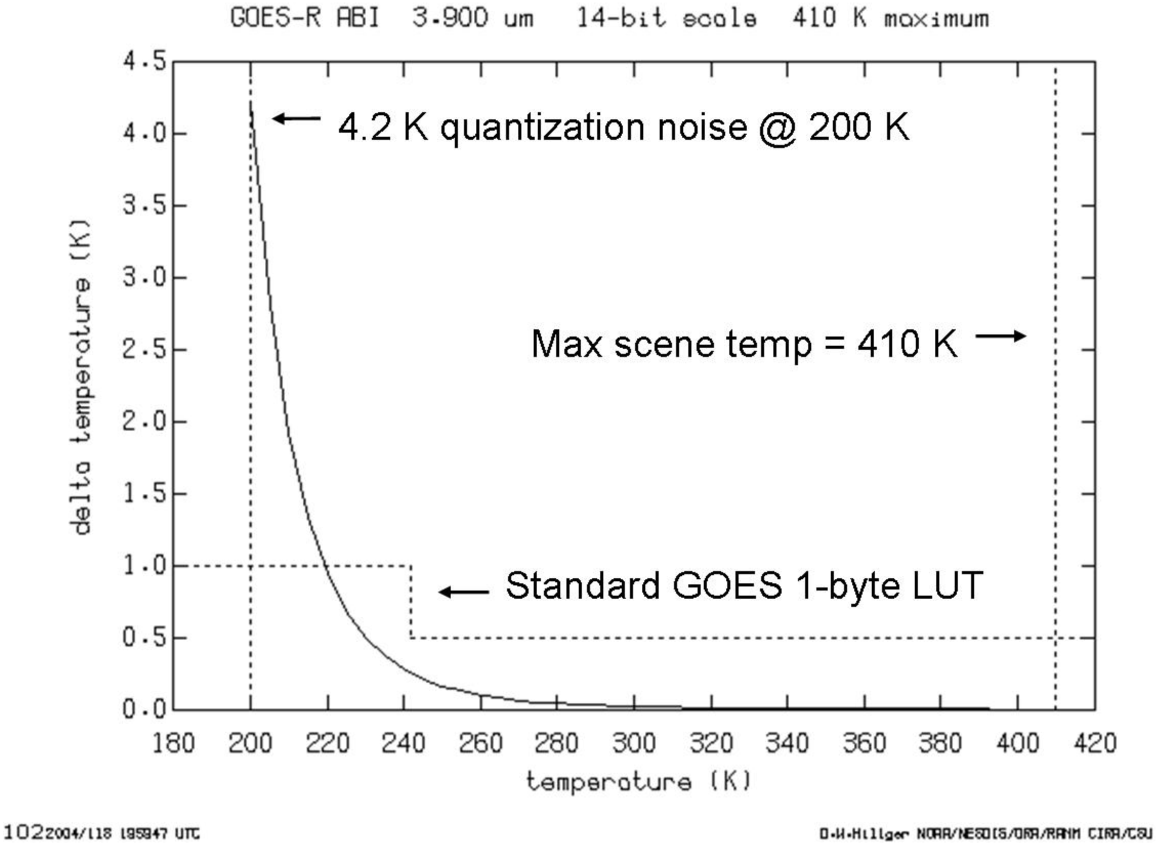

Figure 3: Quantization noise (K) as a function of scene temperature for ABI band-7 (3.9 µm) for a 14-bit scale. Vertical dashed lines are imposed temperature limits. Horizontal dashed line is standard 1-byte count-to-temperature Look-Up-Table (LUT) currently used for GOES data. Temperature precision is not within the desired LUT precision for temperatures below 220 K (-53°C).

5. Conclusion

Although a14-bit scale is probably sufficient for the ABI shortwave infrared band, a 16-bit scale would further ensure that quantization noise would not be a limiting factor for this band. As an alternative, in order to avoid large quantization noise for low temperatures, a non-linear scale could be devised that would tend to equalize the error (in temperature units) as a function of scene temperature. Such a scale, utilizing the same number of bits, would add precision at low temperatures, at the expense of the precision at higher temperatures.

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