Temperature Dependence of Dark Signal for Sentinel-4 Detector

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WS8: Data Processing Chain for Airborne and Spaceborne Sensors

Motivation

- Dark signal is an important parameter for sensor performance
- Has a remarkable temperature dependence
- Optimisation is an important task for scientific detector / sensor

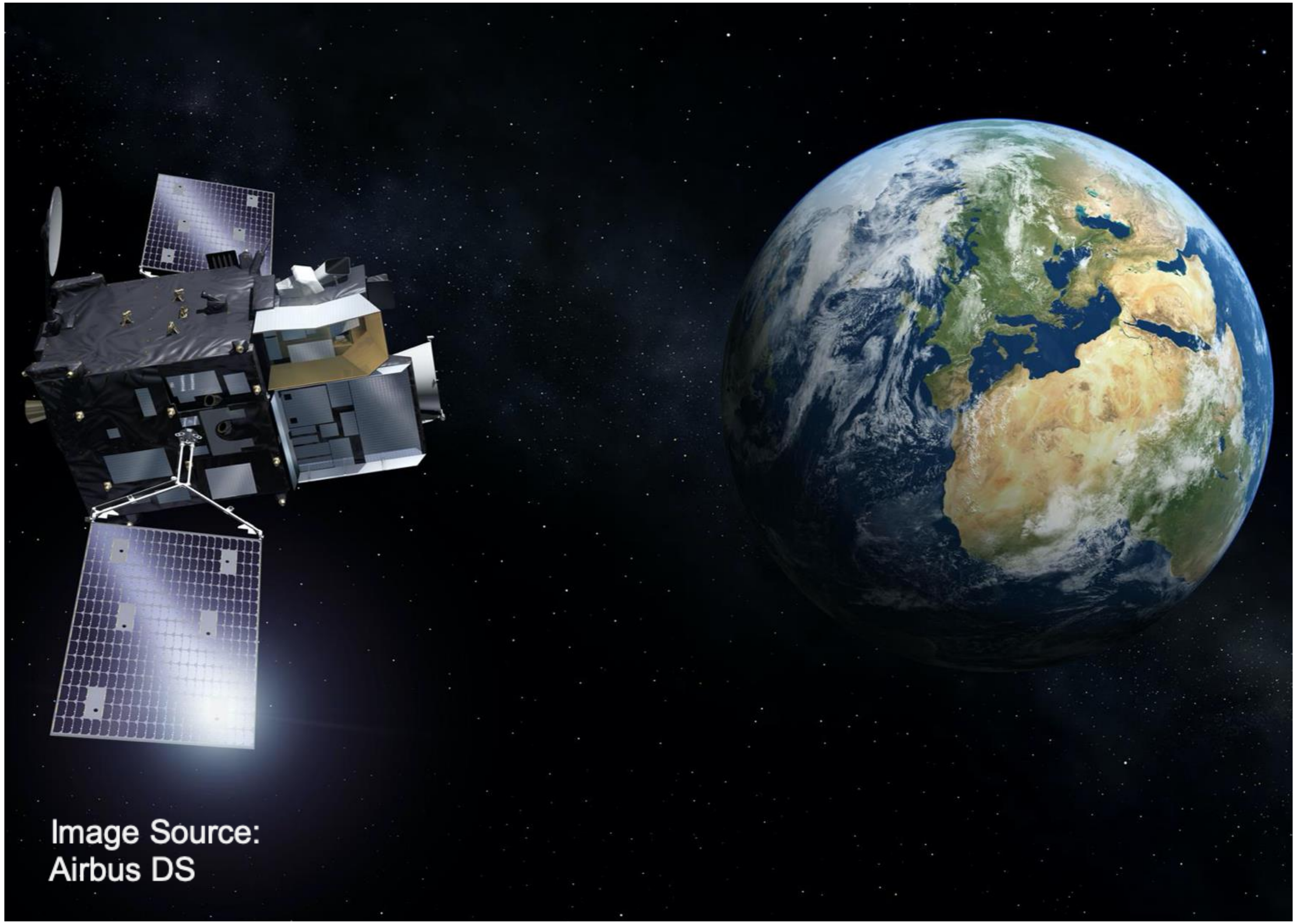
- Modelling is significant for sensor design and calibration
- Modern calibration approach is based on models & measurement / recognition of deviations

- Dark signal measurement was done with Sentinel-4 FPA
- Model test and recognition of deviations from model behaviour

Overview

- Senstinel-4 mission, detector, verification
- Detector Signal Model
- Dark Signal Calculation
- Measurements
- Results
- Discussion & Outlook

Overview - Sentinel 4 Mission



- Part of ESA's COPERNICUS Program (Environmental Surveillance)
- Sentinel 4 → Atmospheric Surveillance
- Hyperspectral Instrument with 2 detectors:
  - UVVIS (305 nm … 500 nm)
  - NIR (750 nm … 775 nm)
- Geostationary orbit above Europe
- East-West Scan in frequency of 1h

Sentinel 4 QM Verification Campaign @DLR Berlin

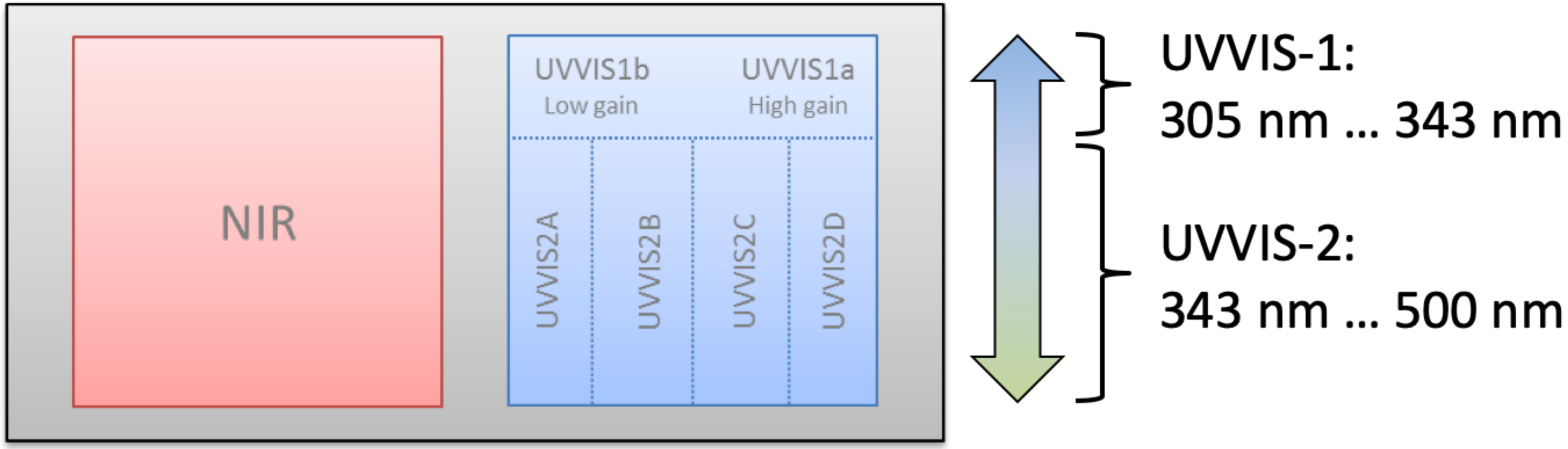
- Verification of Opto-Electronic Payload
- First “Marriage” of FPAs and Front End Electronics after Manufacturing
- Challenging of Opto-Mechanical Boundaries

- Deployment of Thermal Vacuum Chamber (TVC):
- Operating Temperature of Detectors / FPAs = 215 K +/- 5 K
- AR-layers on detectors (without cover glass)
  - Sensitive + Hygroscopic

Detector Design

“Simple” AR-coating on NIR

Graded AR-coating on UVVIS

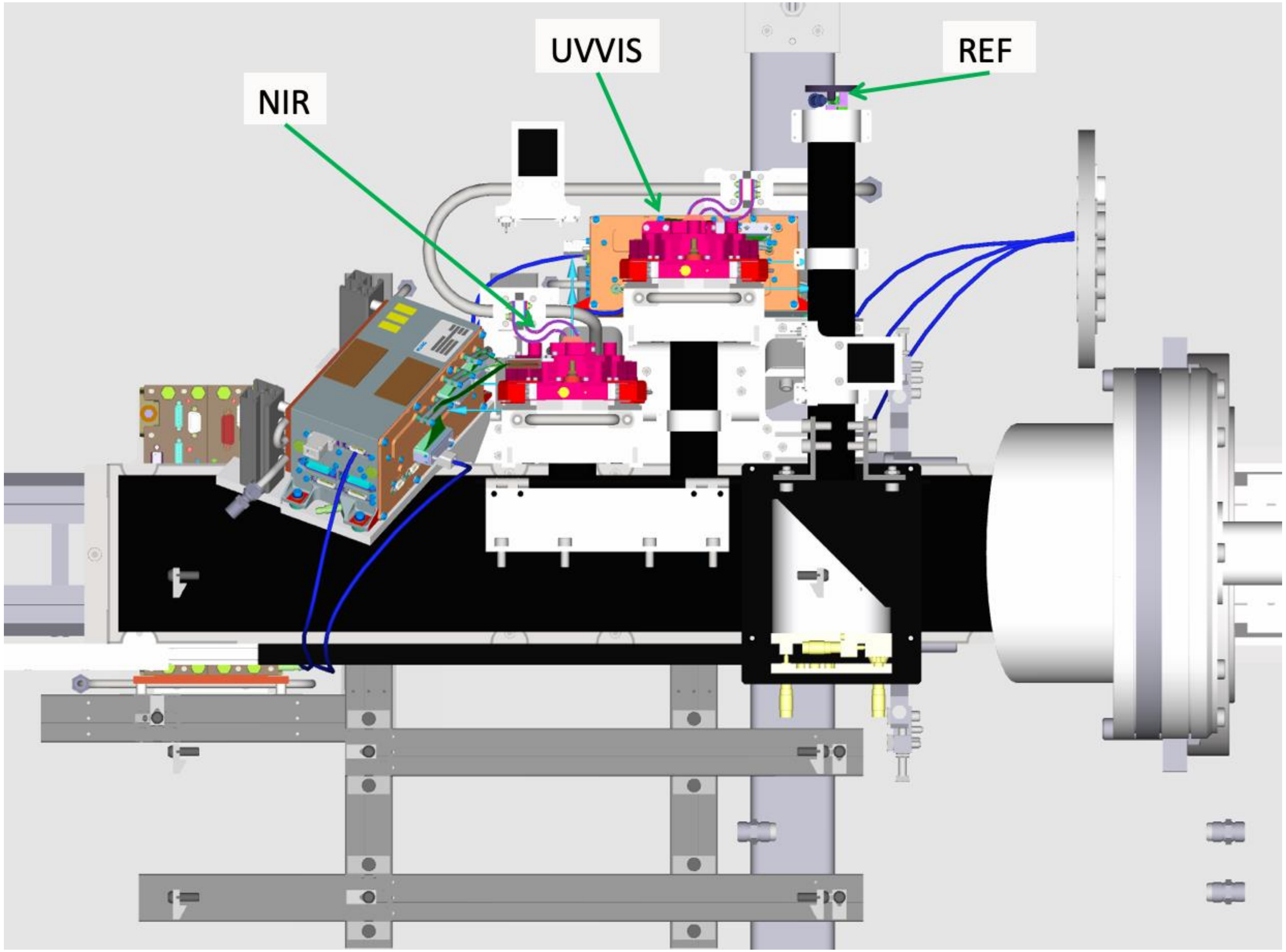


Sentinel-4 detector design of NIR and UV-VIS detector.

- Single point read out on NIR detector
- Separated read-out regimes on UV-VIS detector for
  - Gain adjustment (UVVIS 1)
  - Faster read out (UVVIS 2)

Measurement Setup

- Equal optical path lengths for REF-, UVVIS-, NIR-detector
- Remote flat field Illumination via integrating sphere + filters (Spectr./ND)
- Additionally 635 nm Laser
- Pressure ~ 5*10^-6 mbar
- Two different temperature circuits:
  FPAs:
  210, 215, 220 K and
  273, 283, 293 K
  FEEs and FSE constantly
  293 K
- First „marriage“ of FPAs and FEEs/FSE
- Highly automated test runs



Measurements & Results

Performed Test	Derived Analyses	Result
Linearity	Linearity	✓
	FPS gain / conversion factor	✓
	Full Well Capacity (linear)	✓
	Full Well Capacity (absolut)	✓
	Signal to Noise Ratio	✓
	Charge Transfer Efficiency (Serial)	✓
	Charge Transfer Efficiency (Parallel)	✓
Average Dark Signal	Average Dark Signal	✓
	Dark Signal Non-Uniformity	✓
	Read-out Noise	✓
	Dynamic Range	✓
Memory Effect	Memory Effect	✓
Cross –Talk	Channel to Channel Cross Talk	✓
Stability over 24 h	Stability over 24 h	✓
Random Telegraph Signal	RTS and pixels with high dark noise	✓
FPA LED Calibration	FPA LED Calibration	✓
Quantum Efficiency	QE	✓ (verification of e2v test)
Photo Response Defects	Photo Response Defects	✓ (surface fit correction)
	Photo Response Non-Uniformity	✓ (surface fit correction)

Detector Signal Model for the Average Signal

$$\langle s\rangle = \eta_{DV}\cdot\eta_V\cdot\eta_\lambda^{qu}\cdot\tau\cdot A_{pix}\cdot\frac{\lambda}{hc}\cdot E + DS$$

$\langle s\rangle$	Camera output signal $[DN]$
h	Plank's constant $[Js]$
c	Speed of light $[m/s]$
λ	Center wavelength of incident light $[m]$
$G_S = \eta_{DV}\cdot\eta_V$	Overall system gain $[DN/e^-]$
E	Irradiance at detector level$[W/m^2]$
τ_{int}	Integration time $[s]$
A_{pix}	Pixel area $[m^2]$
DS	Dark signal $[DN]$

- Three noise-components:
  - photon noise,
  - dark current noise, and
  - read-noise.
- Photon and dark current noise are Poisson distributed.

$$\sigma_s^2 = \eta_{DV}^2\cdot\eta_v^2\cdot\left(\langle n_{el}\rangle + \langle n_{el}^D\rangle\right) + \eta_{DV}^2\cdot\sigma_k^2.$$

- Or

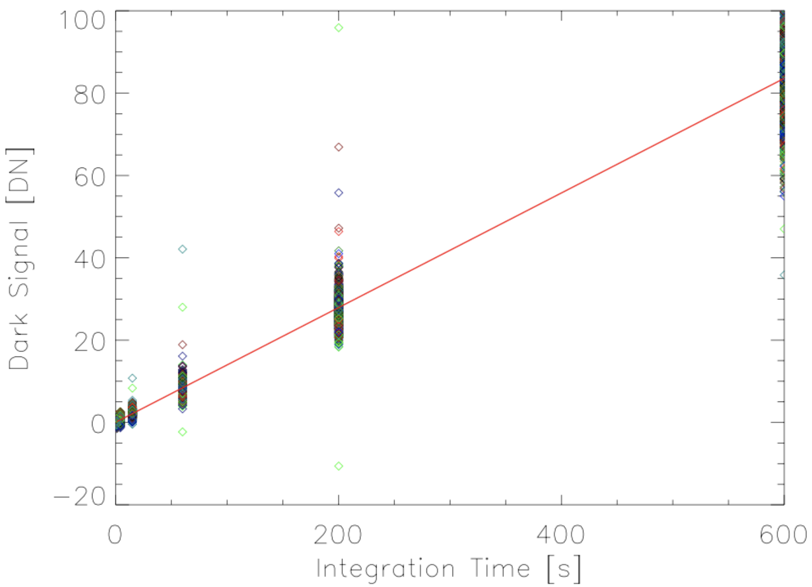
$$\sigma_s^2 = G_S\cdot\langle s\rangle + \eta_{DV}^2\cdot\sigma_k^2$$

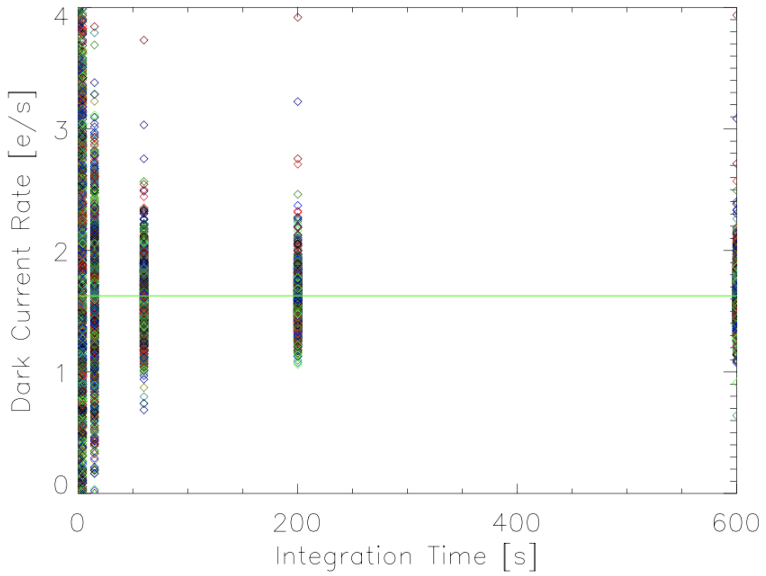
- This linear equation is a relation between variance of measured noise and averaged signal (**PTC -- Photon Transfer Curve**).

Dark Signal Calculation

- Variation of dark signal $D = G_S \cdot \langle n_{el}^D \rangle$ by either the integration time or the operating temperature (→ PTC!)
- Slope of dark signal dependence as a function of integration time

$\sigma_D^2 = D$	Variance of the dark signal
$D = \tau_{\text{int}} \cdot D_R$	Dark signal depends from
τ_{int}	integration time in [s]
D_R	average dark current rate [e/s]





$$D_R\left[nA/cm^2\right] = 10^9 \cdot \left(Q \cdot D_R\left[e/s\right]\right) / A_{pix}$$

$$D_R\left[e/s\right] = D_R\left[nA/cm^2\right] \cdot 10^{-9} \frac{A_{pix}}{Q}$$

Temperature Dependence of the Dark Current Rate

Model from Janesick $D_R = 2.55 \times 10^{15} A_{pix} \cdot D_{FM} \cdot T^{1.5} \cdot e^{-E_g/2kT}$

Empirical model from Skegg $D_R = D_{FM}^{*} \cdot T^{3} \cdot e^{-6400/T}$ *with* $D_{FM}^{*} = D_R\left(T = 300K\right)$

$A_{pix} = 27.5 \cdot 10^{-4} \times 15 \cdot 10^{-4}$	Pixel area $\left[cm^2\right]$
D_{FM}	DC figure-of-merrit @300K in $[e/s]$ or $\left[nA/cm^2\right]$
$E_g = 1.1557 - \frac{7.021 \times 10^{-4} T^2}{1108 + T}$	Silicon bandgap energy $[eV]$
$k = 8.6173324 \times 10^{-5}$	Boltzmann's constant $[eV/K]$
$Q = 1.602176565 \times 10^{-19}$	elementary charge $[C] = [As]$

- Measurements of the dark current with an integration time of $\tau_{int} = 30s$
- Continuous cooling from *293 K* to *215 K* over a period of 12 hours
- After 10 hour cooling stopped and temperatures increased again
- Measurement mode was Long Dark (with separate read-out of image and store areas)
- 42.723 temperature measurements for NIR and VIS detector

Measurements

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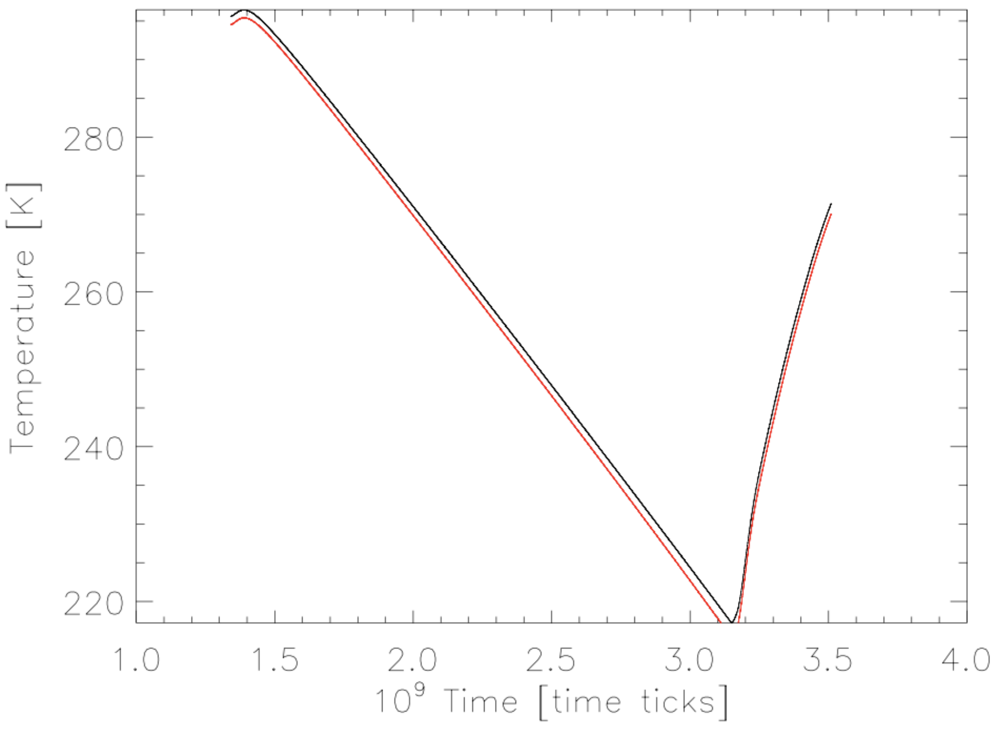
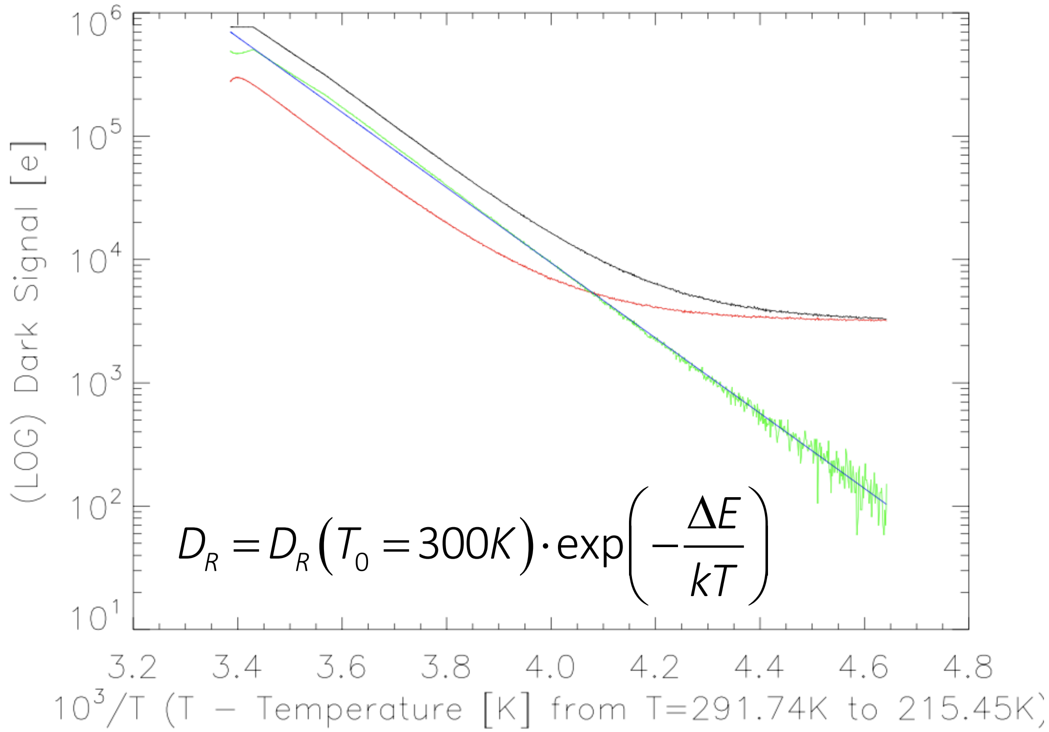
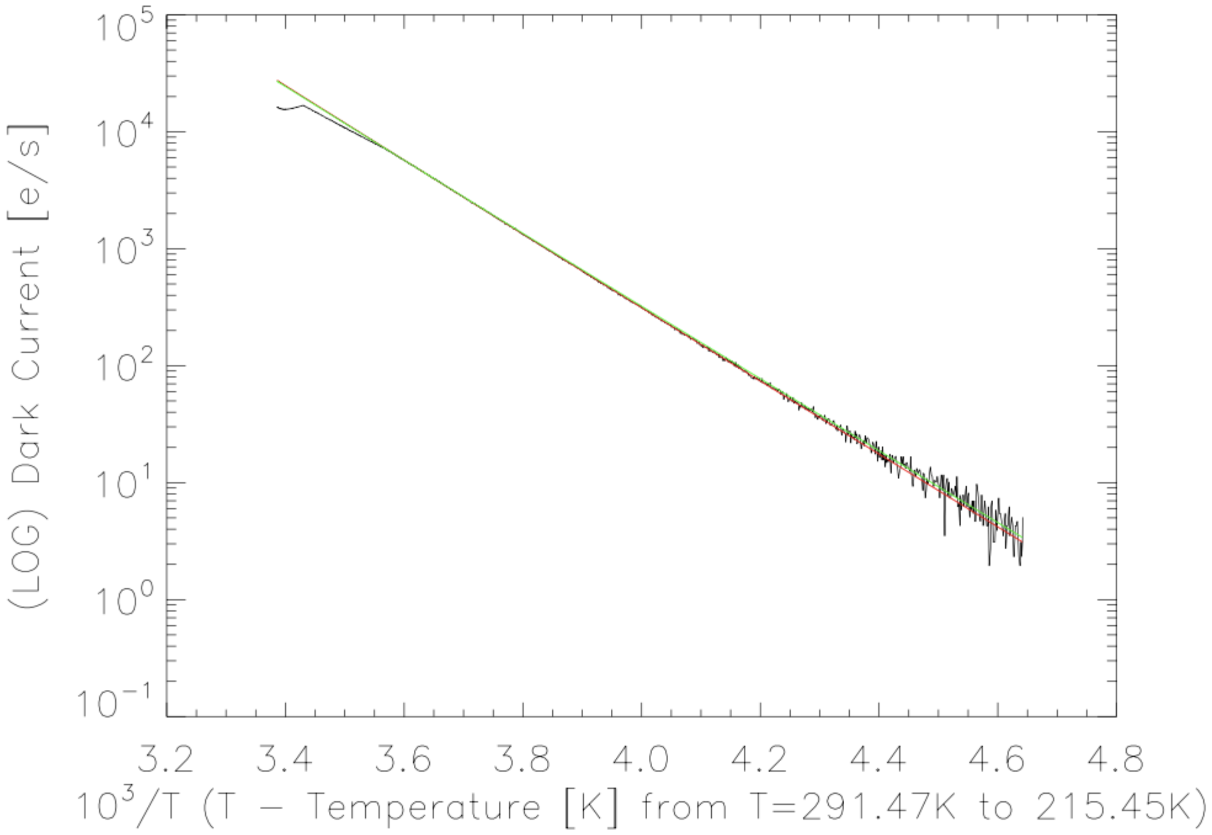
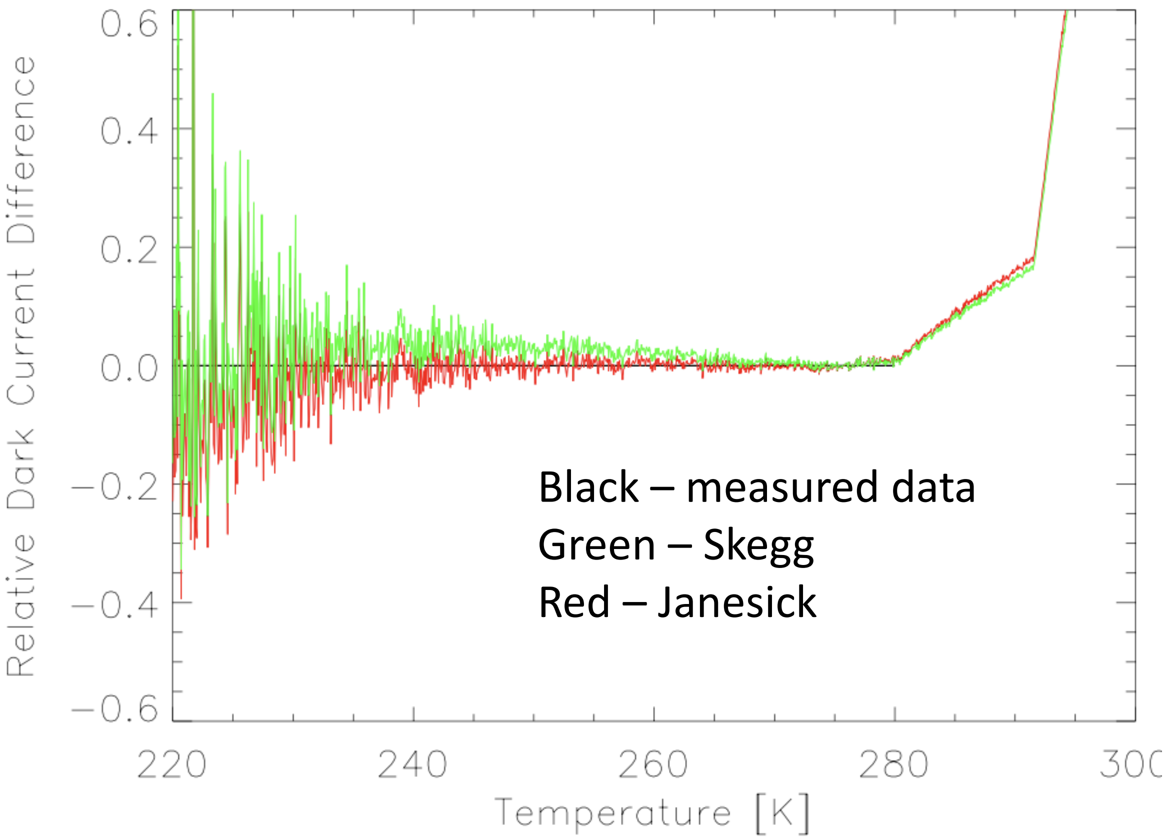




$$D_R = D_R(T_0 = 300K) \cdot \exp\left(-\frac{\Delta E}{kT}\right)$$

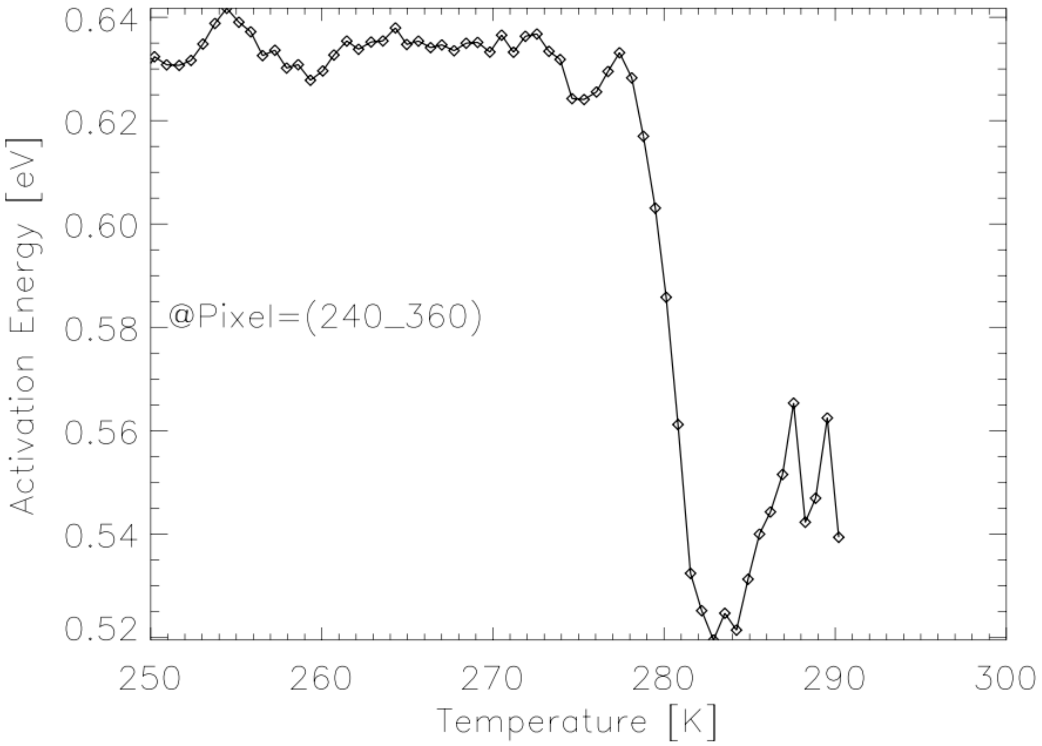
DS - Comparison with Models

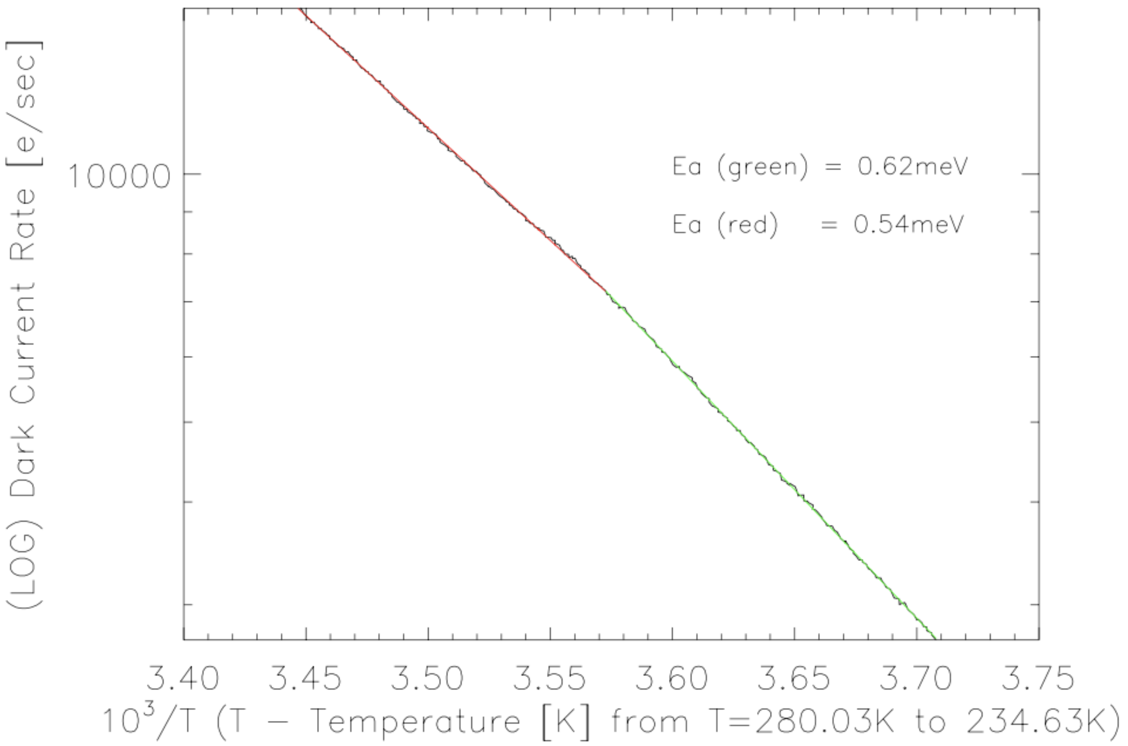




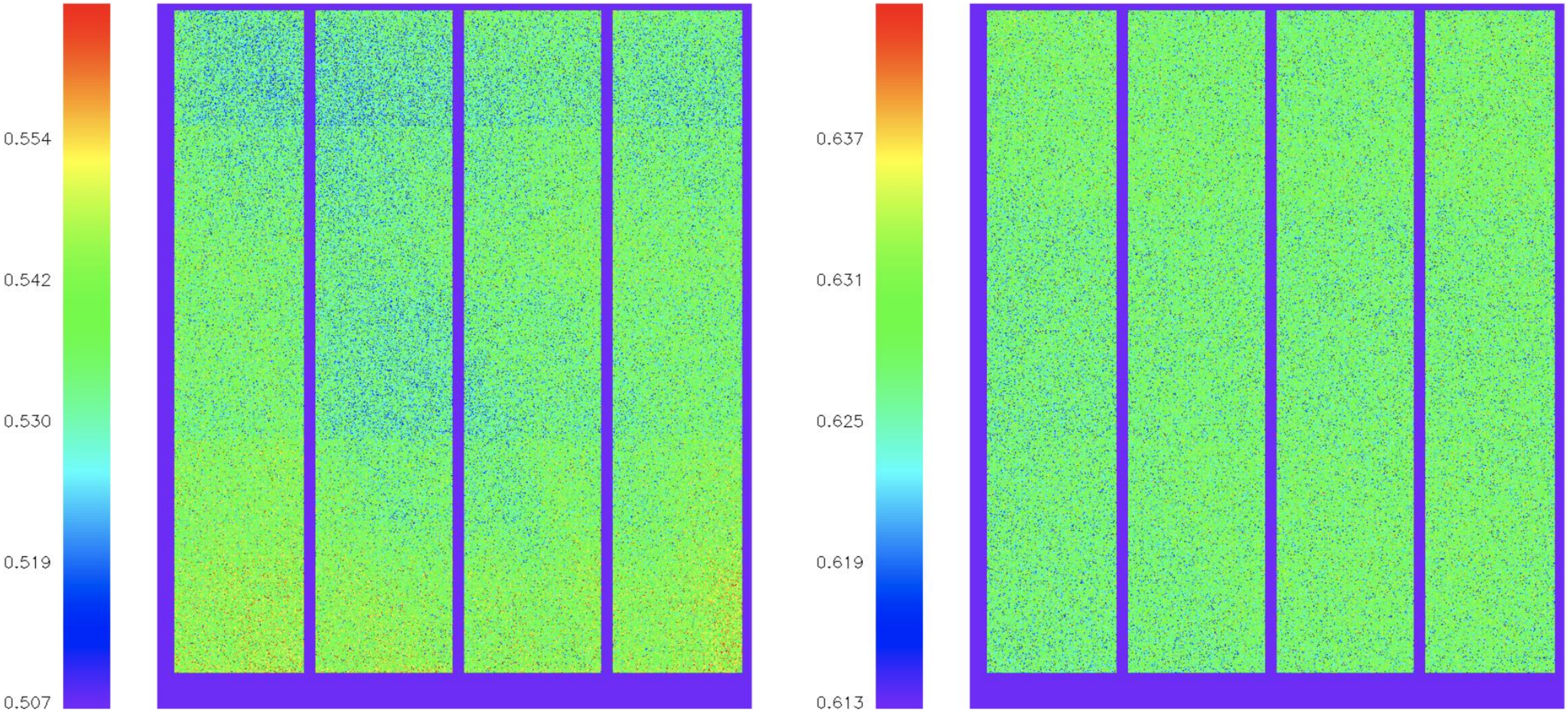
Change of the activation Energy

NIR Temperature Dependence of the Dark Current Rate @Pixel=(240,360). Noticeable is the significant change in the activation energy at 280K



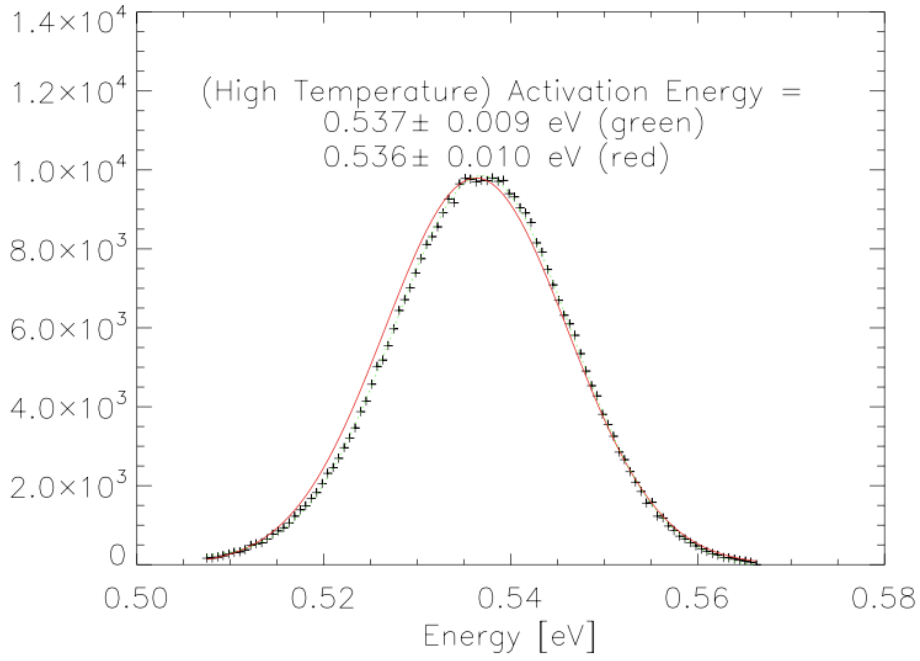


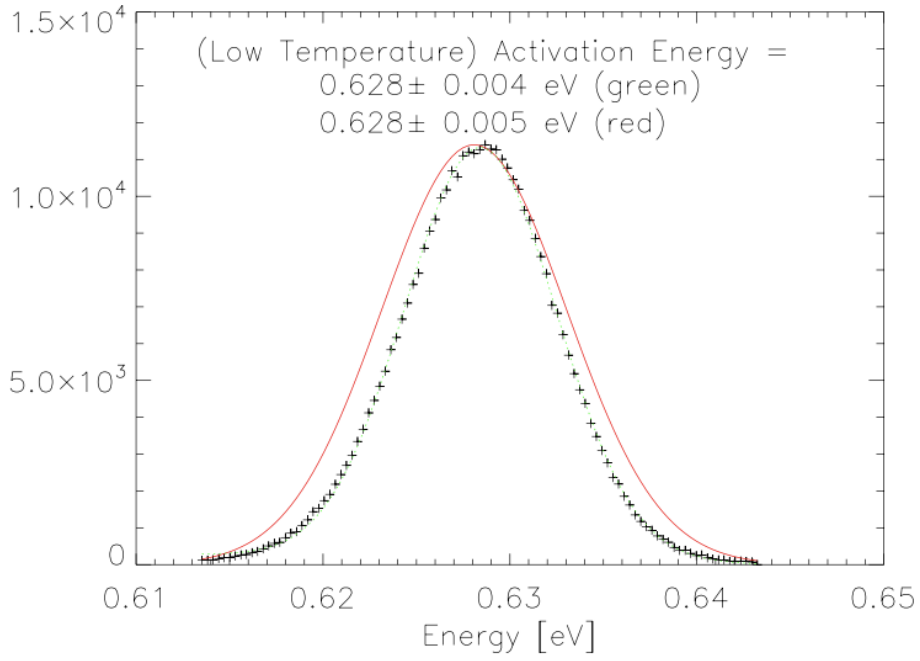
Spatial distribution of the activation eneries



Histogram of the Activation Energy

Histogram values (+), in green a Gauss-fit to the histogram values, red line is the Gauss distribution derived from mean and standard-deviation of the histogram)





Discussion & Outlook

- Investigation of temperature behaviour of the dark signal / current between 215K and 290K for a scientific CCD
- Exceptionally high number of measuring points (900 measurements with an integration time of 30s)
- Basically, the temperature behaviour of the dark current is as expected theoretically and experimentally
- Two parts of the temperature dependence of the dark - can be characterized by different activation energies
- Clear separation of the activation energies at 280K
  - Low temp activation energy = 0.628eV ± 0.004eV
  - High temp activation energy = $0.537eV ± 0.009$eV
- The variation width for the activation energies for the entire chip was extremely small (1% -2%)

Discussion & Outlook

- The main finding of the article is the change of the activation energy from dark current rate with the temperature
- The reason is assumed to be the changing electric field within the silicon chip, since the depletion depth decreases as the number of electrons increases
- Further measurements, which are to be carried out as part of the verification of the flight model, should deepen this knowledge