WFIRST Coronagraph

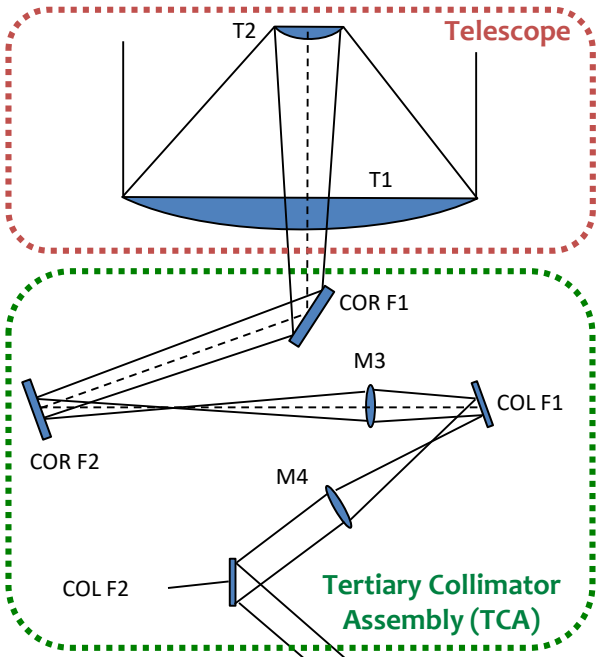
The Effect of Radiation-Induced Traps on the WFIRST coronagraph Detectors

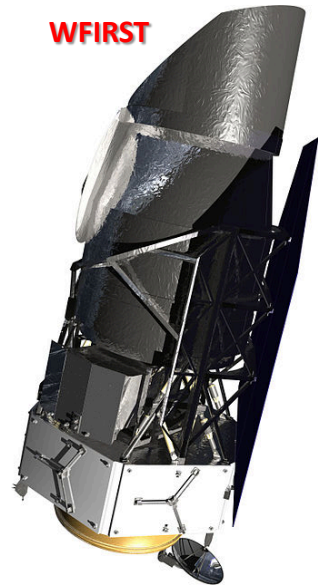
Bijan Nemati,[1]
Robert Effinger,[1] Richard Demers,[1] Leon Harding,[1] Patrick Morrissey[1],
Nathan Bush,[2] David Hall,[2] Jesper Skottfelt,[2]

1: Jet Propulsion Laboratory, California Institute of Technology; Pasadena, CA, USA
2: e2v Center for Electronics Imaging, Open University, Milton Keynes, UK

© 2015 All rights reserved. Email docrev(at)jpl.nasa.gov with any permission, license, or copyright transfer requests.

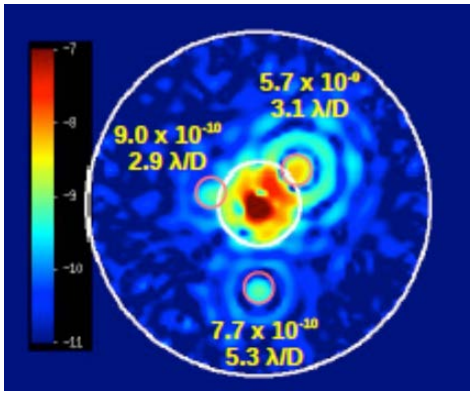
WFIRST Coronagraph and Its Sensors

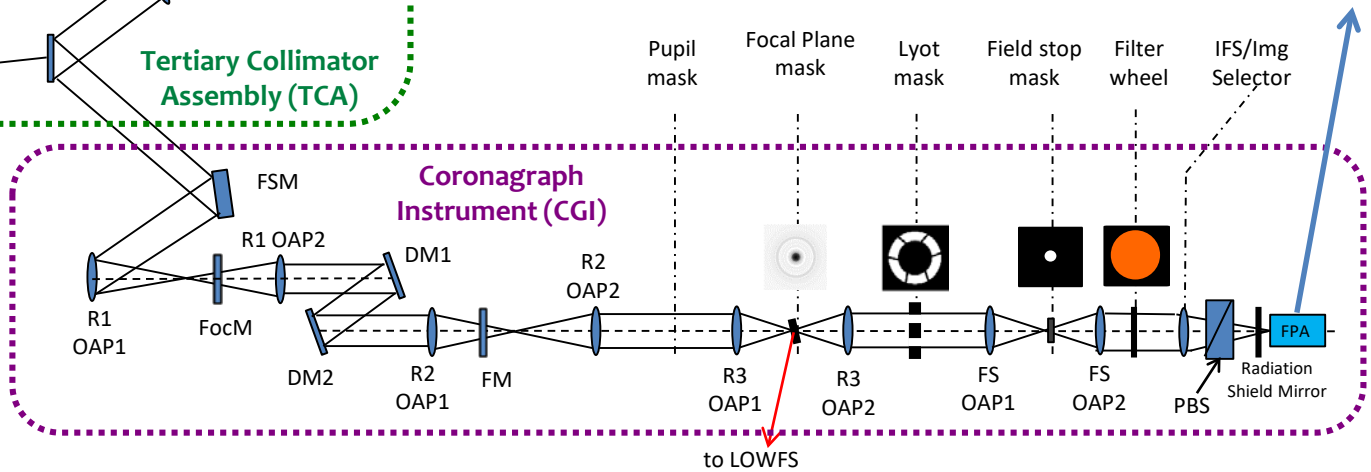




About 1 milli-electron per second per pixel

Model of Dark Hole,
simulated planets are circled in red

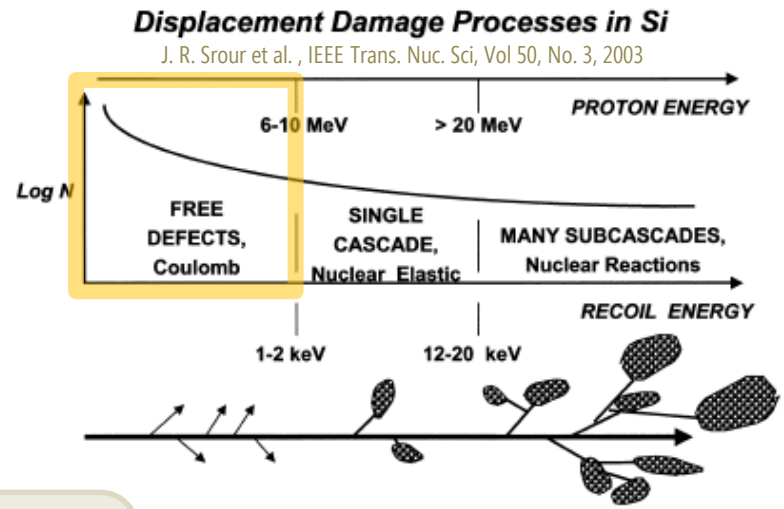


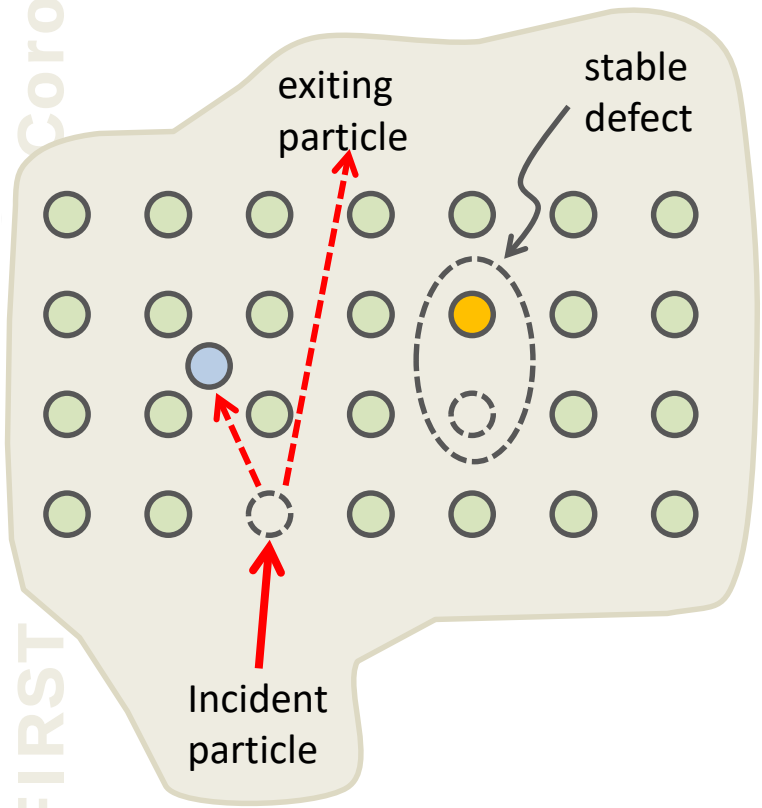


Traps from Radiation Damage

Lattice ions impacted by incoming particles leave behind vacancies or ions in interstitial positions (Frenkel pairs).

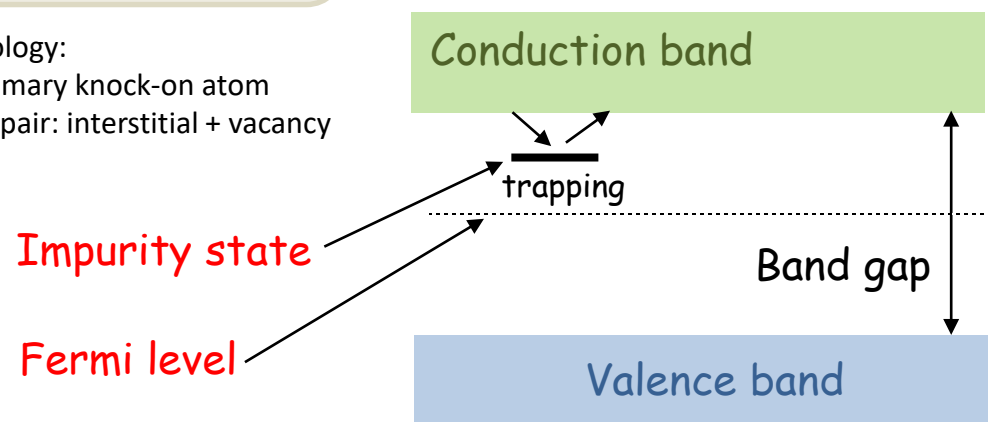
- Low energy particles → point defects
- High energy particles → cluster defects





- dopant or impurity
- interstitial
- vacancy

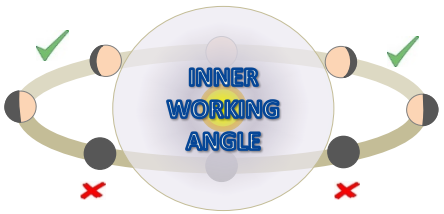
Terminology:
PKA: primary knock-on atom
Frenkel pair: interstitial + vacancy



WFIRST Coronagraph

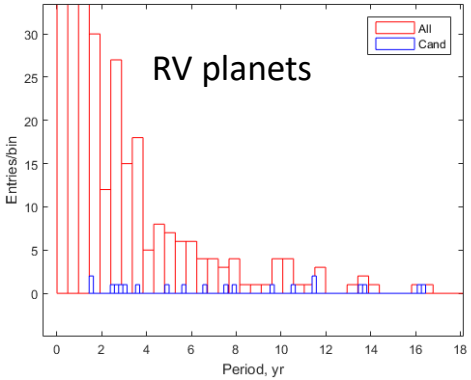
Orbits, Traps and Coronagraphs

- In general the planet is only viewable about 1/3 of the time. At the same time, the typical RV candidate will have an 8 year orbital period.



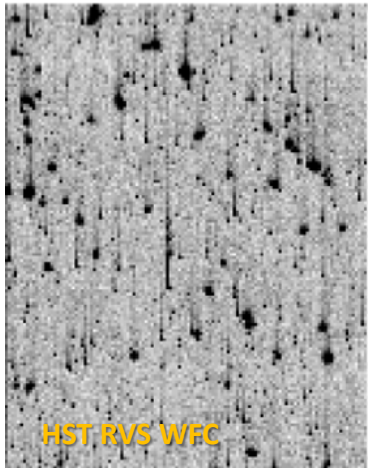
the planet will be observable only ~ 1/3 of the time

- One consequence is that planet observations will necessarily be interspersed throughout the mission lifetime.
  - Some will see a new detector
  - Some will see a detector with traps



- In a CCD, where the parallel clocking process transfers the charge from one row to the next all the way to the readout ("serial") register, the effect of traps is exacerbated since each trap influences signal from upstream pixels in the same column.

- In direct imaging, where we are dealing with objects as dim as 30+ mag, things get even more challenging:
  - Photo-electron rates are at the milli-electrons per second level, so need to integrate a long time to get a signal at all
  - On the other hand, cosmic rays limit exposure times to order 1000 s



Why Are Traps So Important Here

Observing a 20 mag star with conventional telescope

2.4 m Telescope

$$\Phi_{20mag} := fluxCurve(550\ nm, 89\ nm, 20) = 94.011 \cdot \frac{1}{m^2\ s}$$

$$r_{conv} := \Phi_{20mag} \cdot \left(\frac{0.34}{mpix}\right) \cdot A_{col} \cdot \tau_{ref} \cdot \tau_{fil} \cdot QE = 6.859\ Hz$$ electrons per pixel

$mpix = 8.7$

In a 500 sec exposure:

$$n_{conv} := 500\ s \cdot r_{conv} = 3429$$ electrons in 1 pixel in a 500 second exposure

Compare with a typical target planet near a 5 mag star:

WFRIST Coronagraph

$$C_{pl} = 2.874 \cdot 10^{-9}$$

$$\tau_{pl} := \tau_{pup} \cdot \tau_{occ} \cdot \tau_{PSF} \cdot \tau_{ref} \cdot \tau_{fil} \cdot \tau_{pol} = 7.759 \cdot 10^{-3}$$

$$r_{coro} := \Phi \cdot C_{pl} \cdot A_{col} \cdot \frac{\tau_{pl}}{mpix} \cdot QE = 4.895 \cdot 10^{-4}\ s^{-1}$$ electrons per pixel

In a 500 sec exposure:

$$n_{coro} := 500\ s \cdot r_{coro} = 0.245$$ electrons in 1 pixel in a 500 second exposure

Trap Statistics

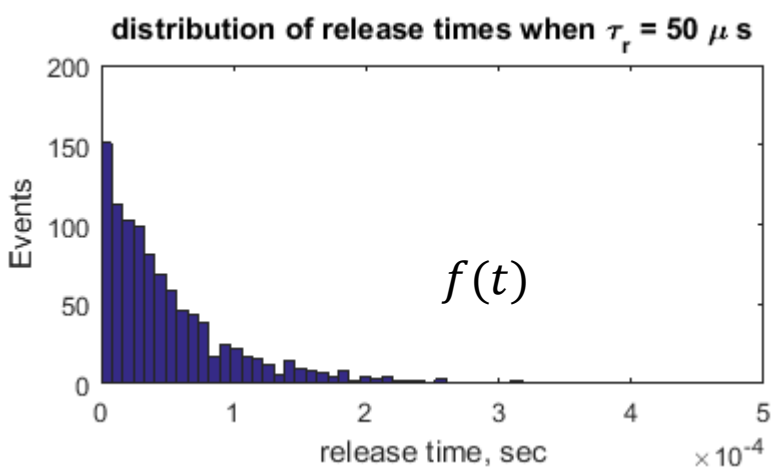
- The strong renewal property and the memoryless property lead to Poisson statistics, with a probability density function given by:

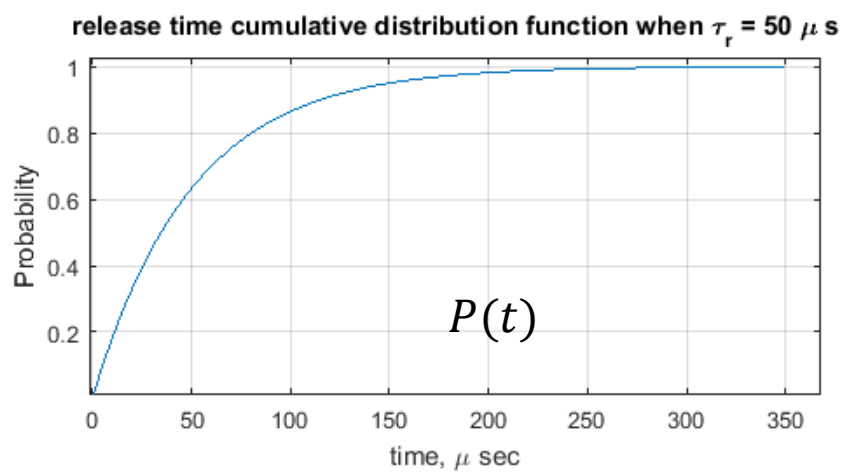
$$f(t) = \frac{1}{\tau_r}\, e^{-t/\tau_r}$$

this is the probability per unit time that a trap release occurs

- Correspondingly, for such a process, the cumulative distribution function is given by:

$$P(t) = \int_0^t \frac{1}{\tau_r}\, e^{t'/\tau_r}\, dt' = 1 - e^{-t/\tau_r}$$





Modeling Electron Capture

- Capture, like release, is governed by the exponential distribution, for which the probability density function (PDF) is given by:

$$\frac{dP_c}{dt} = \tau_c \, e^{-t/\tau_c}$$

PDF

- Integrating this leads to the probability that after some passage of time, the capture has occurred, which is cumulative distribution function (CDF):

$$P_c(t) = \int_0^t \tau_c \, e^{-\frac{t'}{\tau_c}} \, dt'$$

CDF

$$= 1 - \exp(-t/\tau_c)$$

- The capture time depends on the electron density near the trap n_e, the trap capture cross-section σ, and the electron thermal velocity v_{th}:

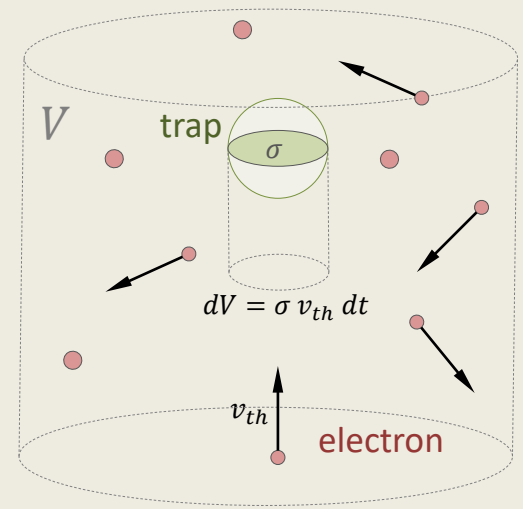
$$\tau_c = \frac{1}{\sigma \, v_{th} \, n_e}$$

Motivation: Consider a volume V around a trap. Relative to each electron, in time *t*, the trap subtends a volume. On average, when the entire volume has been sampled once, we expect a single hit.

If τ_c is the time required for the local e- population to sample the entire volume V:

$$(n_e V) \, \sigma \, v_{th} \, \tau_c = V$$

$$\rightarrow \quad \boxed{\tau_c = \frac{1}{\sigma \, v_{th} \, n_e}}$$



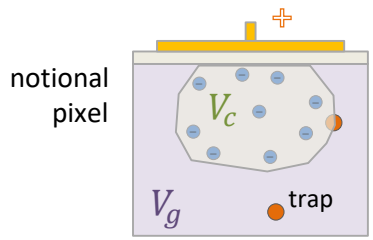
Capture – II

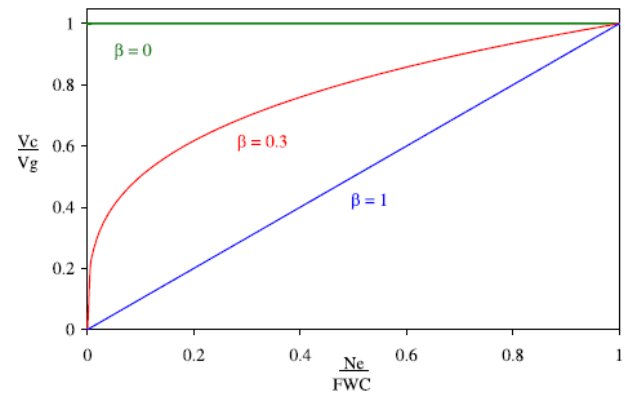
- If we assume that the electron density is given by the charge packet population N_e divided by the confinement volume V_c, then:

$$n_e = \frac{N_e}{V_c}$$

- We can parameterize the growth of V_c with N_e given full well capacity N_{fw} , per Alex Short et al., as:
  - V_g is the available volume of the pixel, the max V_c can be.
  - $\beta = 1$ for constant density situation; $\beta = 0$ for constant volume

$$\frac{V_c}{V_g} = \left(\frac{N_e}{N_{fw}}\right)^{\beta}$$





- The thermal velocity of the electron is given by:

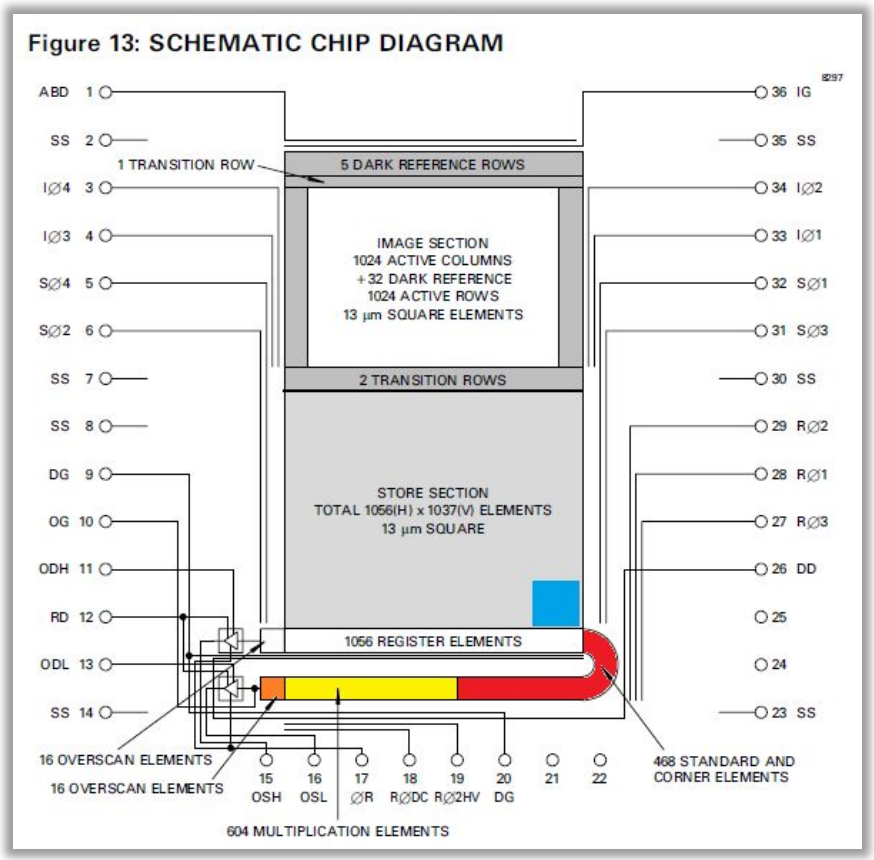
$$\frac{1}{2} m_e^* v_t^2 = \frac{3}{2} kT \rightarrow \quad v_t = \sqrt{\frac{3kT}{m_e^*}}$$

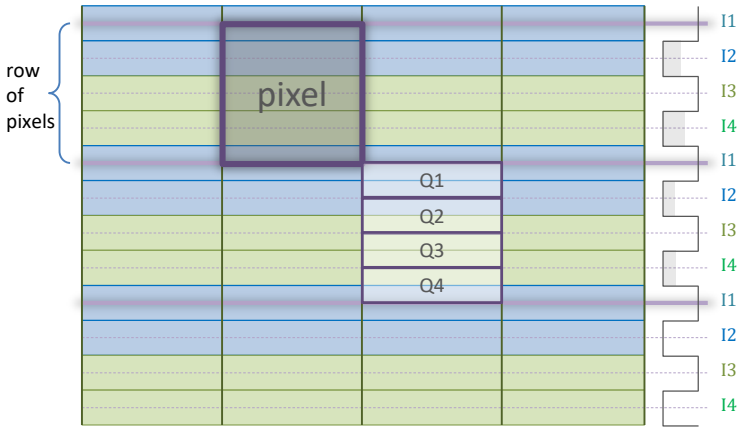
- Putting it all together:

$$P_c(t) = 1 - e^{-t/\tau_c} \qquad \tau_c = \gamma\, N_e^{\beta-1} \qquad \gamma = \frac{V_g}{\sigma \sqrt{\frac{3kT}{m_e^*}}\, N_{fw}^{\beta}}$$

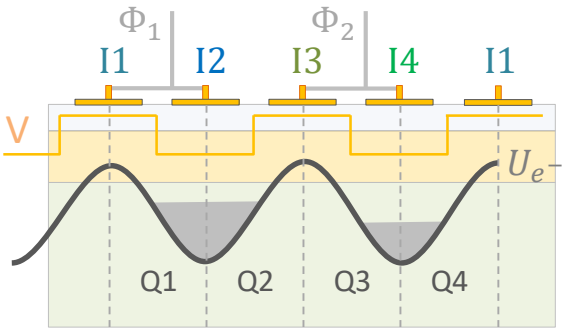
Modeling Traps For the CCD-201 (EMCCD)

- Break down image region into quadrants
- There are 2 charge packets per pixel – these determine where the electrons get released and hang around to get recaptured





CCD201 is a pseudo 2-phase clocking CCD



CCD201 Pseudo 2-Phase Clocking

Two-phase image pixel charge transfer showing potential under gates. I1 and I2 clocked together. I3 and I4 clocked together. Barrier phases I1 and I3 prevent charge from transferring backwards.

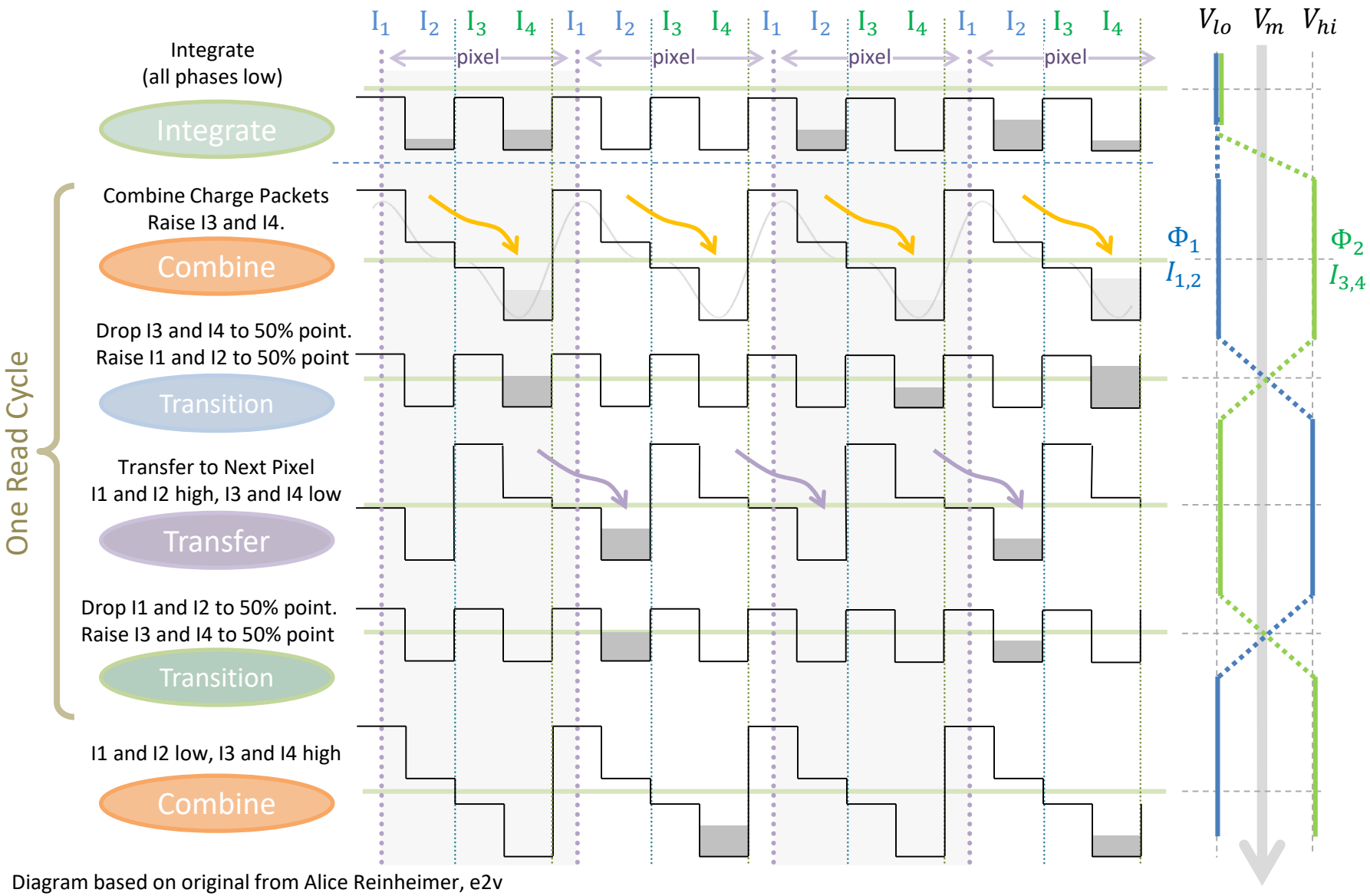
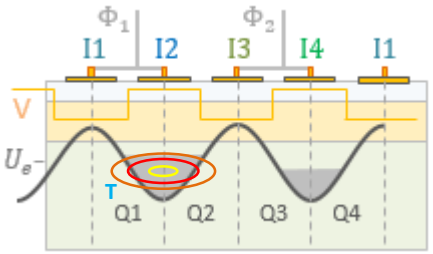


Diagram based on original from Alice Reinheimer, e2v

Trap Model: Release – Sweep – Capture

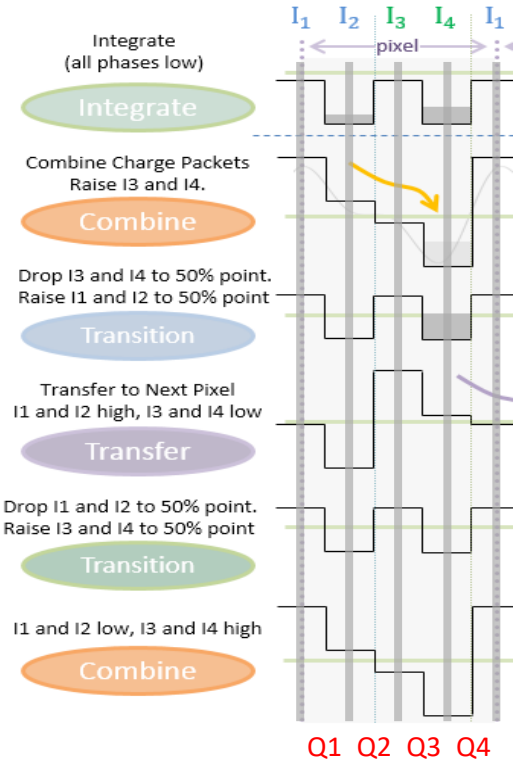



```
for irow = 1: sensor.Npix

    % COMBINE ================== (~0.5 us)
    % charge packets under I2 are moved to combine with those in I4
    % assume no recapture occurs during the short time of this step
    % except under I4: the potential gradient under the other
    % electrodes sweeps everything to under get I4
    % In each pixel, packet#1 is under I2 and packet#2 is under I4

    % release electrons according to the packets the charges will
    % be swept to after release
    relOpts.sensor = 'CCD201'; relOpts.region='frame';
    [relElecPackets, traps] = trapRelease(Durations.combine, sensor, traps, relOpts);

    % Update the ccd gate packet contents by the released electrons
    sensor.gatePackets = sensor.gatePackets + relElecPackets;

    % combine the two packets for each pixel
    combinedPackets = pixelate(sensor.gatePackets, 'sum', 2, 1);
    % reconstruct the gatePackets (fill in the empty gates)
    sensor.gatePackets = reshape([zmtx(:),combinedPackets(:)]',sensor.Npix*sensor.nPack,[]);

    % calling capture after sweep means capture only occurs
    % under gate 4 in this step
    capOpts.sensor = 'CCD201'; capOpts.region = 'frame';
    [sensor, traps] = trapCapture(Durations.combine, sensor, traps, capOpts );

    % TRANSITION A ============= (~0.25 us)
    % Transition A is an intermediate state as the phase voltages
    % are swung to reverse state. At mid-point this looks like a
    % short version of integrate state, with 1->2 and 3->4, except
    % the duration is so short that no photo-conversion is assumed
    % to occur.
```

Release

Sweep

Capture



How the Trap Capture is Implemented

```
indempty = find(traps.frame.occupied==0);
for iempty = 1: length(indempty)
    itr = indempty(iempty);

    % How many electrons are available for capture near this trap?
    Nelec = sensor.gatePackets(traps.frame.packetRows(itr), traps.frame.cols(itr));

    if Nelec > 0
        % capture time constant goes as sqrt of no. of electrons in the vicinity
        % generate a random capture time with the appropriate time constant
        % for derivations see B. Nemati trap presentation, March 2016
        tau1 = sensor.packetMaxVolume / (traps.frame.crossSection(itr) ...
               * sensor.thermalVelocity * sensor.fullWellCapacity^sensor.volBeta) ;
```

Compute capture time constant:

```
        tauCapture =  Nelec^(sensor.volBeta-1) * tau1;
```

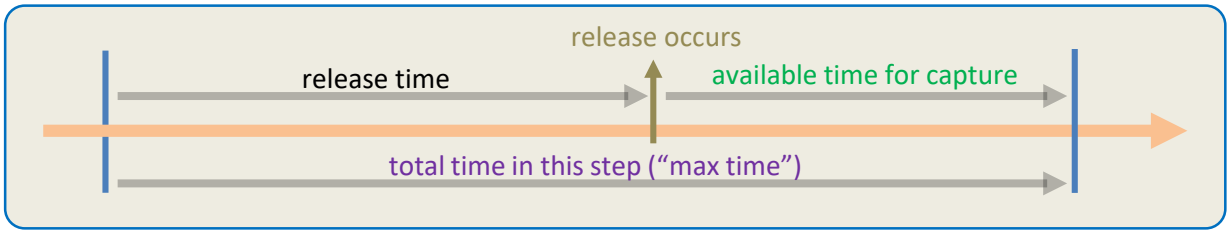
Random instance of capture time:

```
        captureTime = randexp2(tauCapture);
```

$$PDF(t) = \frac{1}{\tau_c}\, e^{-t/\tau_c}$$

Available dwell time:

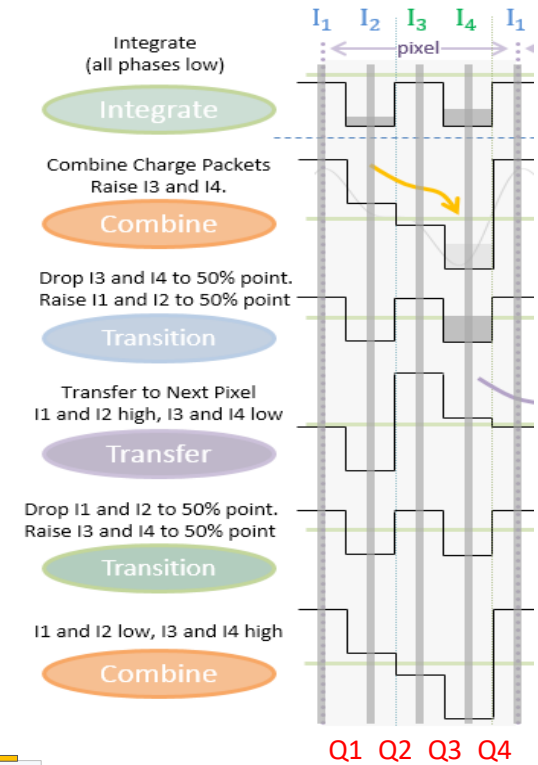
```
        availableTime = (maxTime - traps.frame.releaseTime(itr));
        if captureTime < availableTime
            traps.frame.occupied(itr) = 1;
            sensor.gatePackets(traps.frame.packetRows(itr), traps.frame.cols(itr)) = ...
                sensor.gatePackets(traps.frame.packetRows(itr), traps.frame.cols(itr)) - 1;

        end
    end
    % this was the opportunity in this step for the trap to capture or
    % release. Now reset the release time for this step
    traps.frame.releaseTime(itr) = 0;
end
```

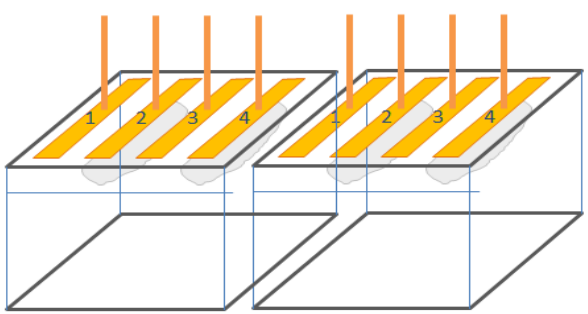


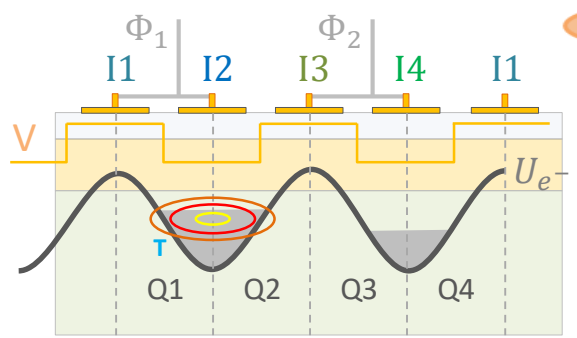
Sweep Table

- What happens to a released electron, depending on where the trap is located, and which phase of CCD we are in:

Trap under:	Q1 + Q2	Q3 + Q4
Integrate O(1000 s)	Sweep to Packet 1	Sweep to Packet 2
Combine (500 ns)	To Packet 2 immediately	Sweep to Packet 2
Transition (250 ns)	Sweep to Packet 1	Sweep to Packet 2
Transfer (500 ns)	Sweep to Packet 1	To Next Packet 1 immediately

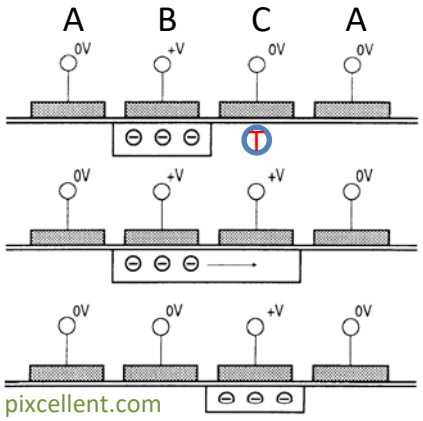




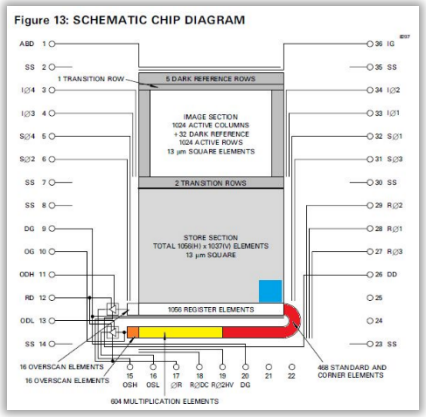


General Paradigm for Serial Register Model

- Shift in one row of pixels from the frame:
  - six clock steps per transfer of one pixel
  - each clock step is broken down to three main parts: Release, Sweep, Capture
- To capture, the trap must:
  - be empty
  - be near a charge packet with $n_{e^-} > 0$
  - the location of the charge packet, relative to the location of the trap must satisfy the conditions in the table below
  - The trap capture time must be short enough



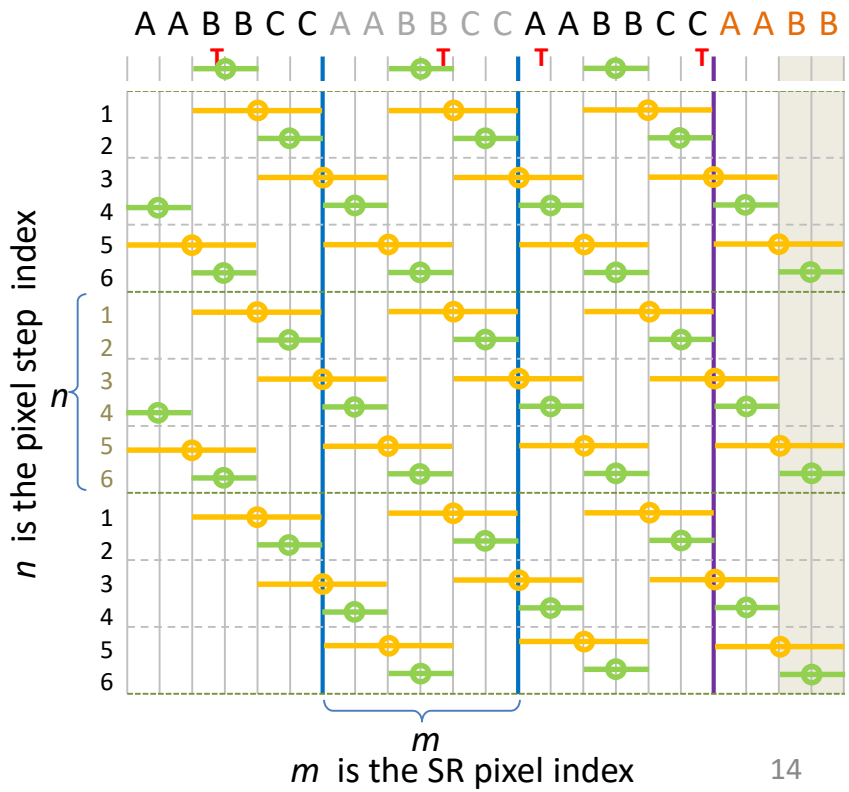
pixcellent.com



Capture Rules

Table of charge packet assignments to trap locations at a given readout step *n*

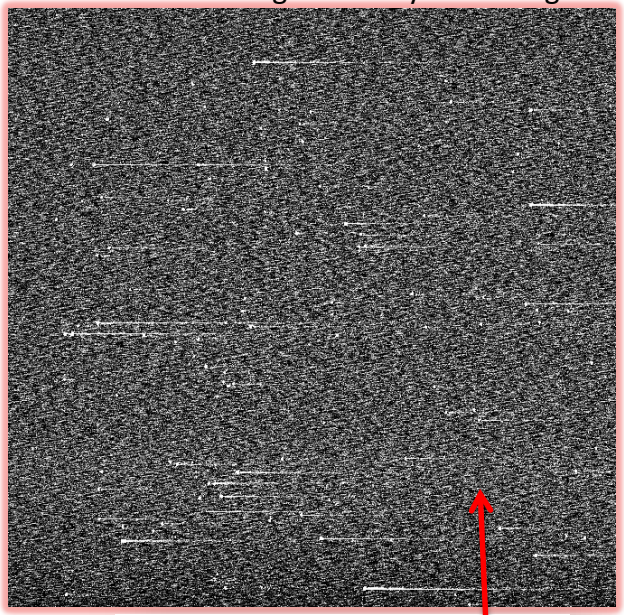
pixel step	gate step	sub step	A 1	A 2	B 3	B 4	C 5	C 6
n	1	Com BC	x	x	m-n+1	m-n+1	m-n+1	m-n+1
	2	Isolate C	x	x	x	x	m-n+1	m-n+1
	3	Com CA	m-n	m-n	x	x	m-n+1	m-n+1
	4	Isolate A	m-n	m-n	x	x	x	x
	5	Com AB	m-n	m-n	m-n	m-n	x	x
	6	Isolate B	x	x	m-n	m-n	x	x

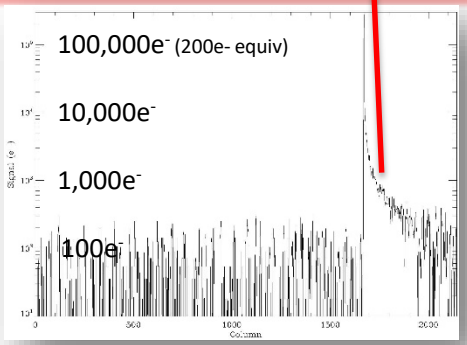


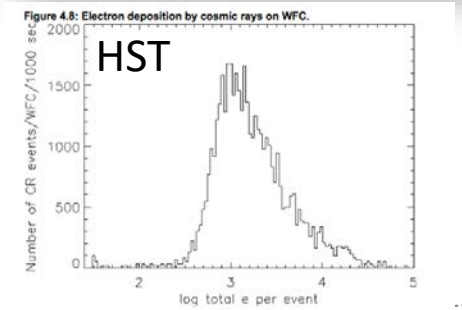
Cosmic Rays Limit Frame Exposure Times

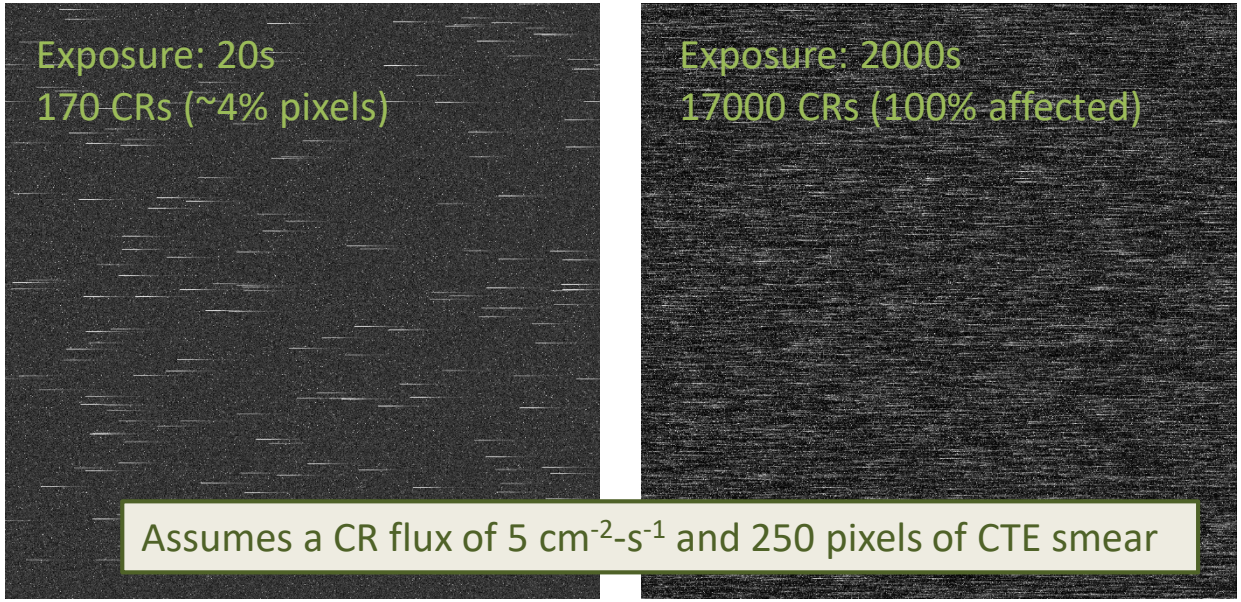
- Full frame science-grade CCD201 image.
  - Temp = -85 °C (188 K)
  - Gain = 500
  - Exposure = 500s
  - Read Noise = 90e$^-$
- Observed tails extend hundreds of pixels, disappearing into the large read noise
  - Tails will be worse at 165K
  - Tails will be worse at higher gain
  - Tails will consume multiple rows
  - There will be many more in space

Image courtesy L. Harding







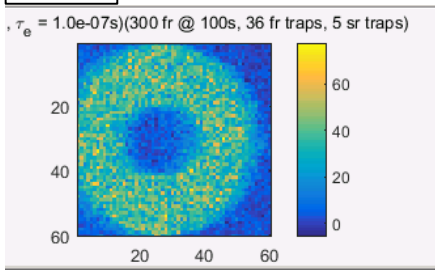


Assumes a CR flux of 5 cm^{-2}-s^{-1} and 250 pixels of CTE smear

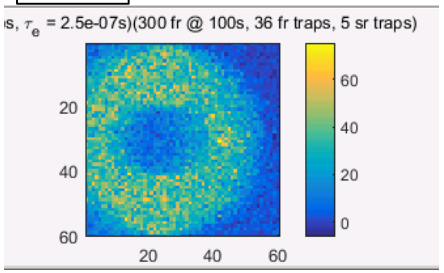
Fractional RMS Error vs. Trap Release Time

(with 1% Frame and Serial Traps)

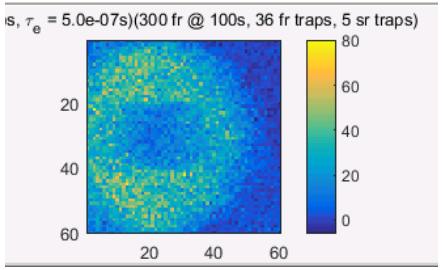
100 ns



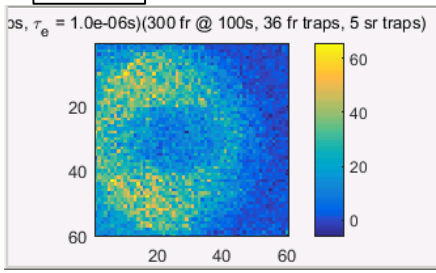
250 ns



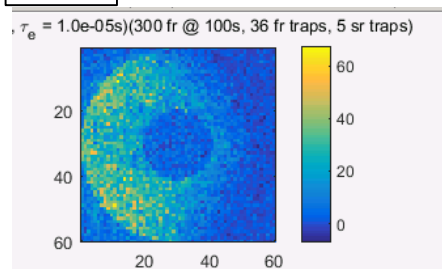
500 ns



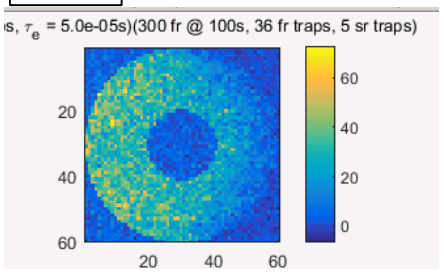
1 us



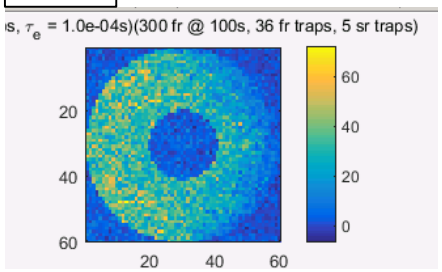
10 us



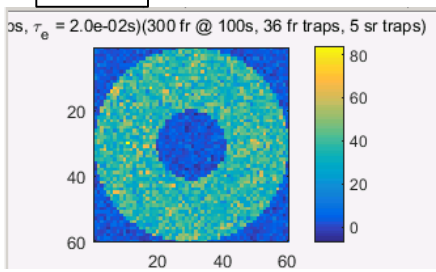
50 us



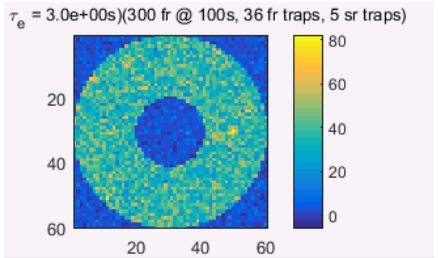
100 us



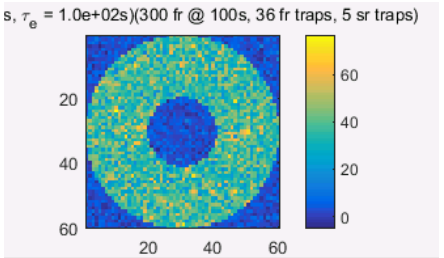
20 ms

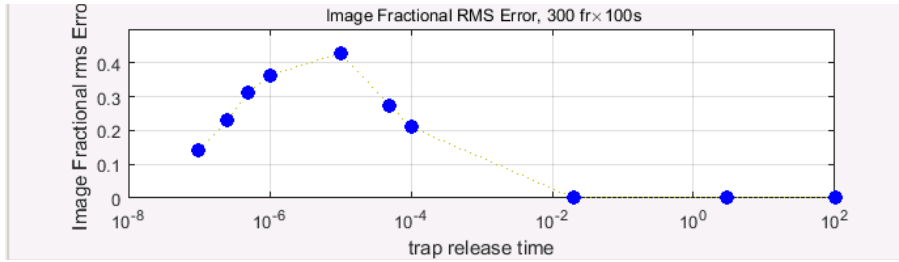


3 sec



100 sec

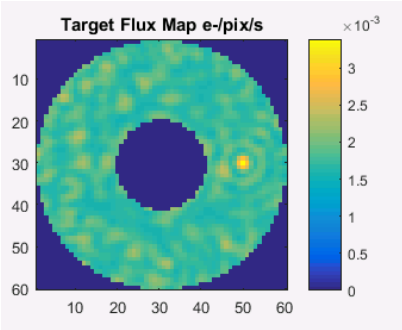


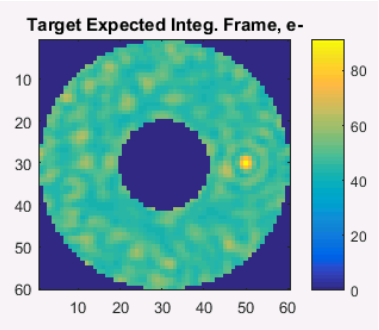


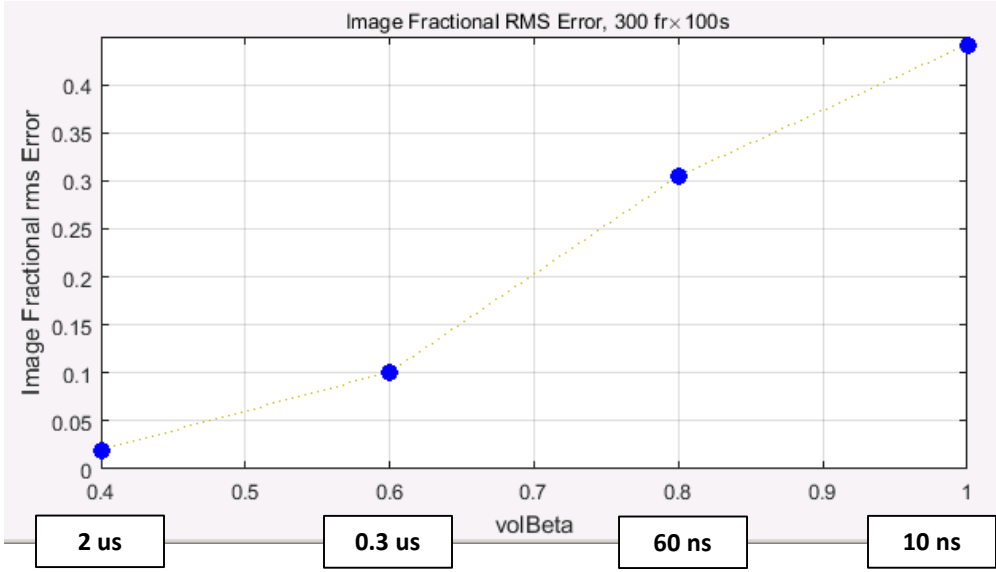
Fractional RMS Error vs. Trap Capture Time

(with 1% Frame and Serial Traps)

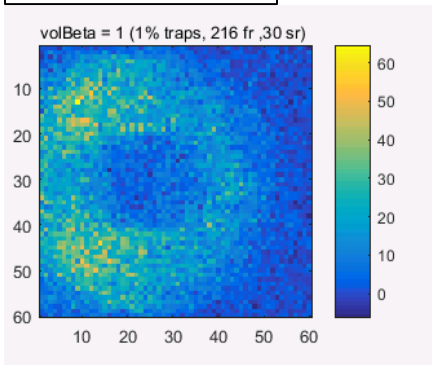
- Fast trap capture times cause the most image degradation



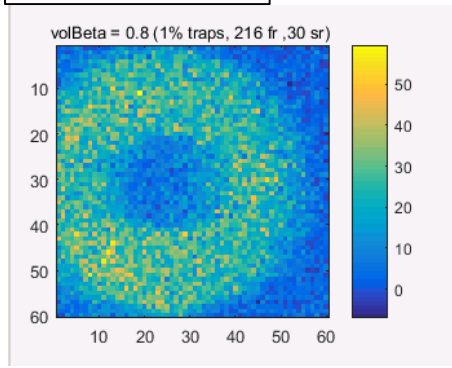




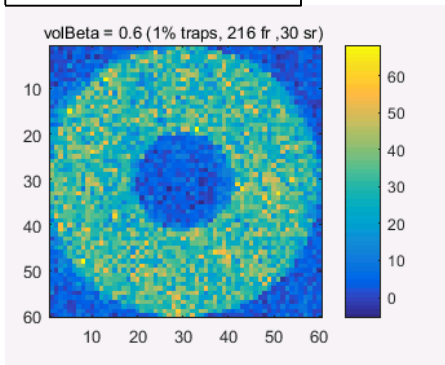
Tau_capture = 10 ns



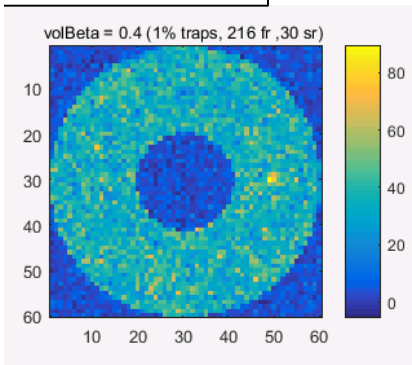
Tau_capture = 60 ns



Tau_capture = 0.3 us



Tau_capture = 2 us



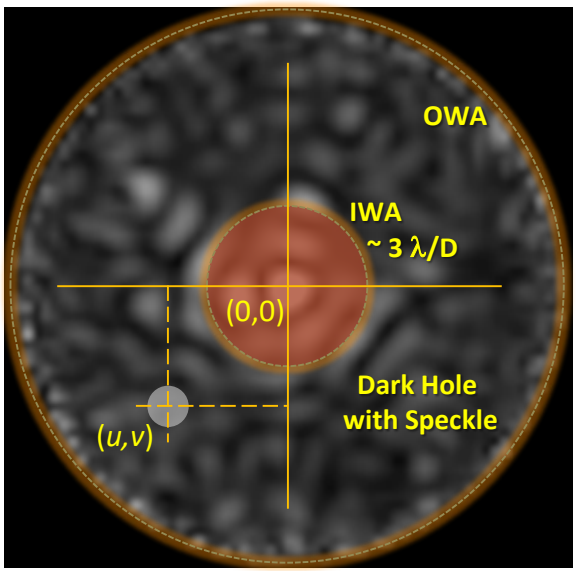
Mitigating Effects of Traps

- To mitigate the effects of traps some steps can be taken:
- Detector can be kept warm while not in use
  - Approximately 80% of the time, WFIRST will be doing dark energy observations with the wide angle instrument: coronagraph not used
  - Beam test results indicate that cosmic ray induced traps are much less likely to occur when the detector is warm
- Observations can be front-loaded
  - Observing early in the mission can help
- Shielding will be maximized
  - Shielding does help, though there is a limit to how effective it can be

BACKUP

Direct Imaging and Dark Hole Size

- Direct imaging of the exo-system will involve placing the dark hole (in 2 polarizations) on the CCD



~ 60 - 100 pixels

evaluate | source

$$C_{CG}(u,v) \equiv \frac{I_{star}(u,v;0,0)}{I_{star}(u,v;u,v)}$$

- The IFS will take up the entire CCD – same number of photons spread over far more pixels!