The Compute and Control for Adaptive Optics (cacao) real-time control software package

Arnaud Sevin,
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Damien Gradatour

Observatoire de Paris / (France)

Software engineering & development
Integration with COMPASS simulation environment, RT hardware (GPU, FPGA) and RT processes management/monitoring

SCExAO Subaru Coronagraphic Extreme Adaptive Optics

Olivier Guyon, Julien Lozi,
Nour Skaf

Subaru Telescope / SCExAO
(US, Japan)

cacao development and On-sky testing for ExAO applications

Hatem Ltaief & Dalal Sukkari
KAUST (Saudi Arabia)

HPC expertise
Develop and provide linear algebra libraries for Machine Learning

Users / co-developers

Keck Observatory
Sylvain Cetre

Facility-class AO (NGS & LGS)

Kernel project/OCA
Frantz Martinache

Focal plane WFS/C

MagAO-X
Jared Males

Extreme-AO

Subaru Telescope
Christophe Clergeon

Facility-class AO (NGS & LGS)

Alison Wong & Barnaby Norris

Machine learning / AI
Neural Networks

cacao's goals

Support today & tomorrow's off-the-shelf powerful computing hardware
→ manycore systems (CPU, GPU) and FPGAs
→ high performance computing engine to requirements of large scale AO systems

.. and advanced AO systems and algorithms
→ flexible modular software architecture
→ scalable solution
→ built-in (and growing) machine learning support for predictive control, sensor fusion
→ facilitates asynchronous links between sensors and loops
→ full speed telemetry to disk for post-processing
Foreseen applications : Extreme-AO, MCAO, Tomographic AO ...

Community effort, fully open-source
→ no proprietary / closed source roadblocks
→ enables easy/quick implementation of new algorithms
→ adopts standard data stream format

Easy to adopt and use: short path from ideas to real-time implementation
→ abstract away / hide HPC complexity
→ manage challenging real-time timing constraints for the user
→ provide high-level GPU/CPU configuration

Current Status

Provides low-latency to run control loops

→ Use mixed CPU & GPU resources, configured to RTC computer system

On SCExAO, control matrix is 14,000 x 2000. Matrix-vector computed in ~100us using 15% of RTC resources @ 3kHz

Portable, open source, modular, COTS hardware

→ No closed-source driver

→ std Linux install (no need for real-time OS)

→ using NVIDIA GPUs, also working on FPGA use

→ All code on github: **https://github.com/cacao-org/cacao**

Easy for collaborators to improve/add processes

→ Hooks to data streams in Python or C

→ Template code, easy to adapt and implement new algorithms

→ Provide abstraction of link between loops

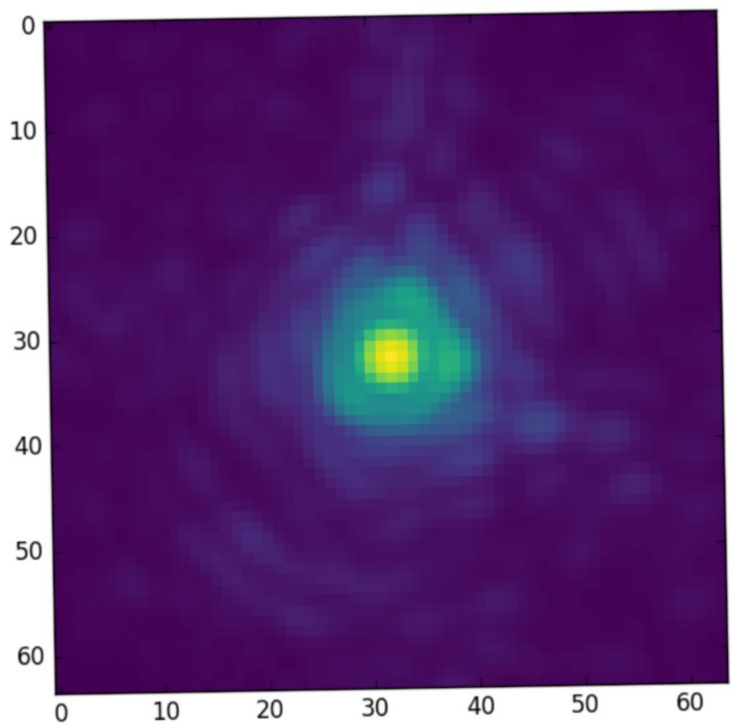
→ Toolkit includes viewers, data logger, low-latency TCP transfer of streams

cacao RTC: current status
& on-sky performance for ExAO

Supports high frame rate conventional ExAO operation

SCExAO: 1200 modes corrected at 3.5 kHz
(input: 120x120 Pyramid image,
output: 2000 actuator DM)

On-sky visible image (750nm), log scale (VAMPIRES)



Supports advanced operation modes for enhanced science performance … Why ?

Mixed CPU/GPU solution provides ample computing power and also supports advanced operation modes:

- **Model-free predictive control** using machine learning approach → **deeper contrast, fainter stars**

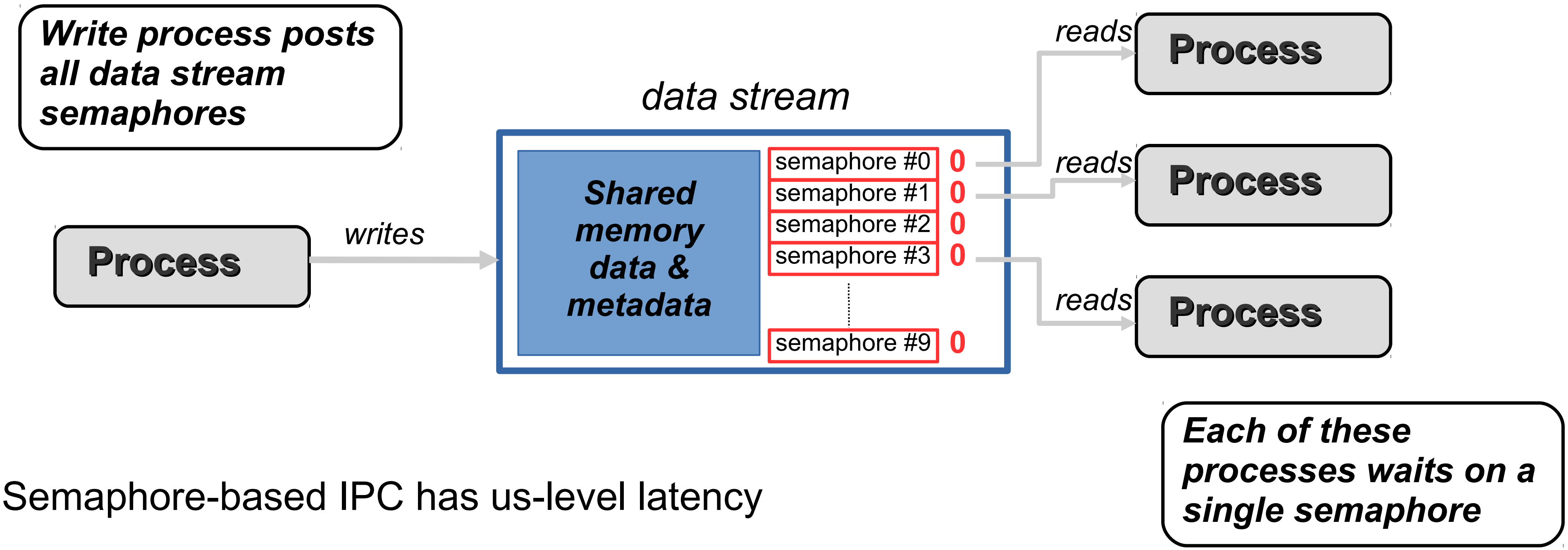
- **On-sky response matrix acquisition** while loop is running (<2 sec to acquire 2000-mode response matrix) → improved calibration → **higher performance control**

- **Real-time links between control loops, sensor fusion** → **speckle control, low-order modes correction**

Main Guiding Principle: data owns IPC
Processes sign up to semaphores

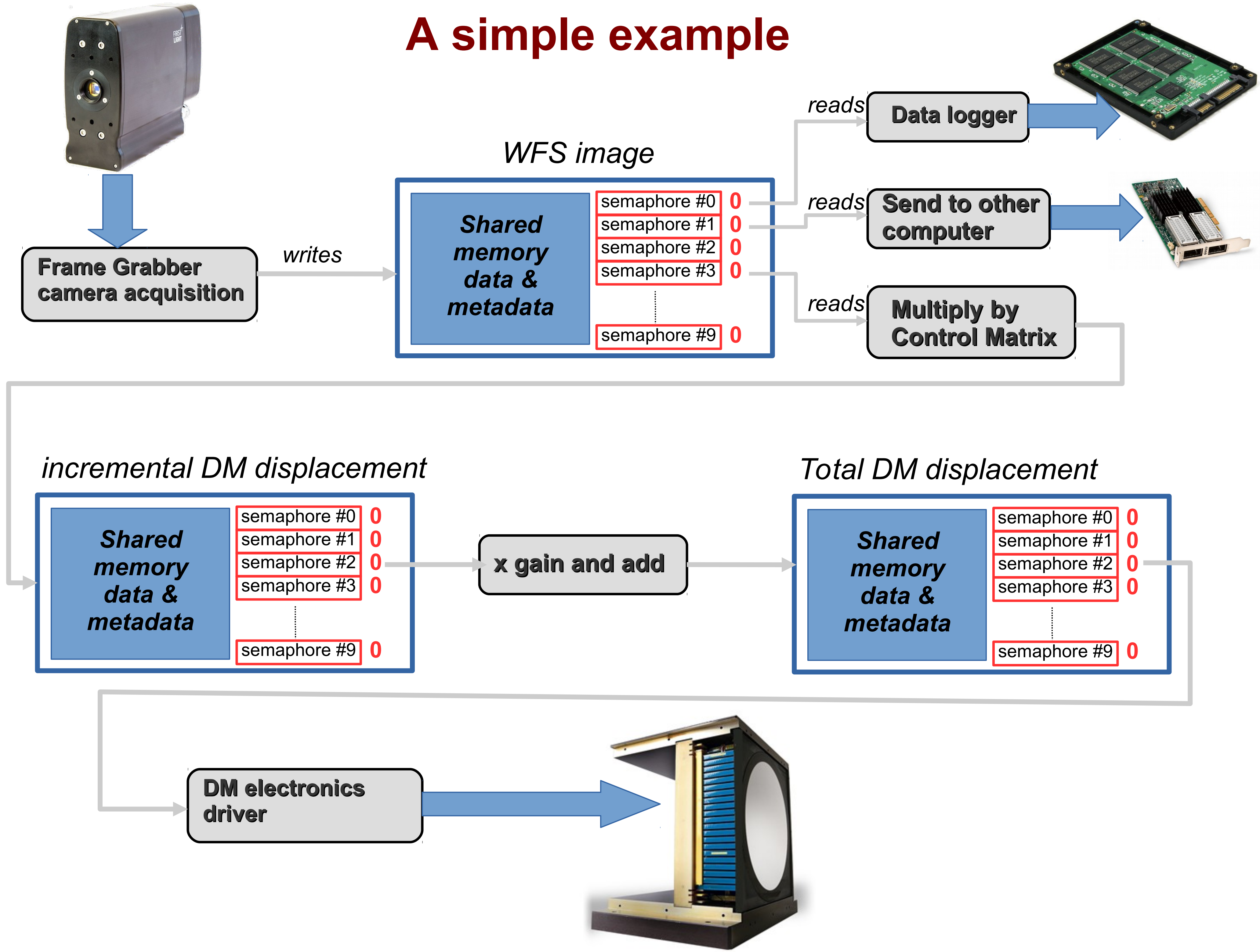
Build AO control loop as a finite set of CPU-mananged processes.
Processes can manage computations on GPGPU(s)

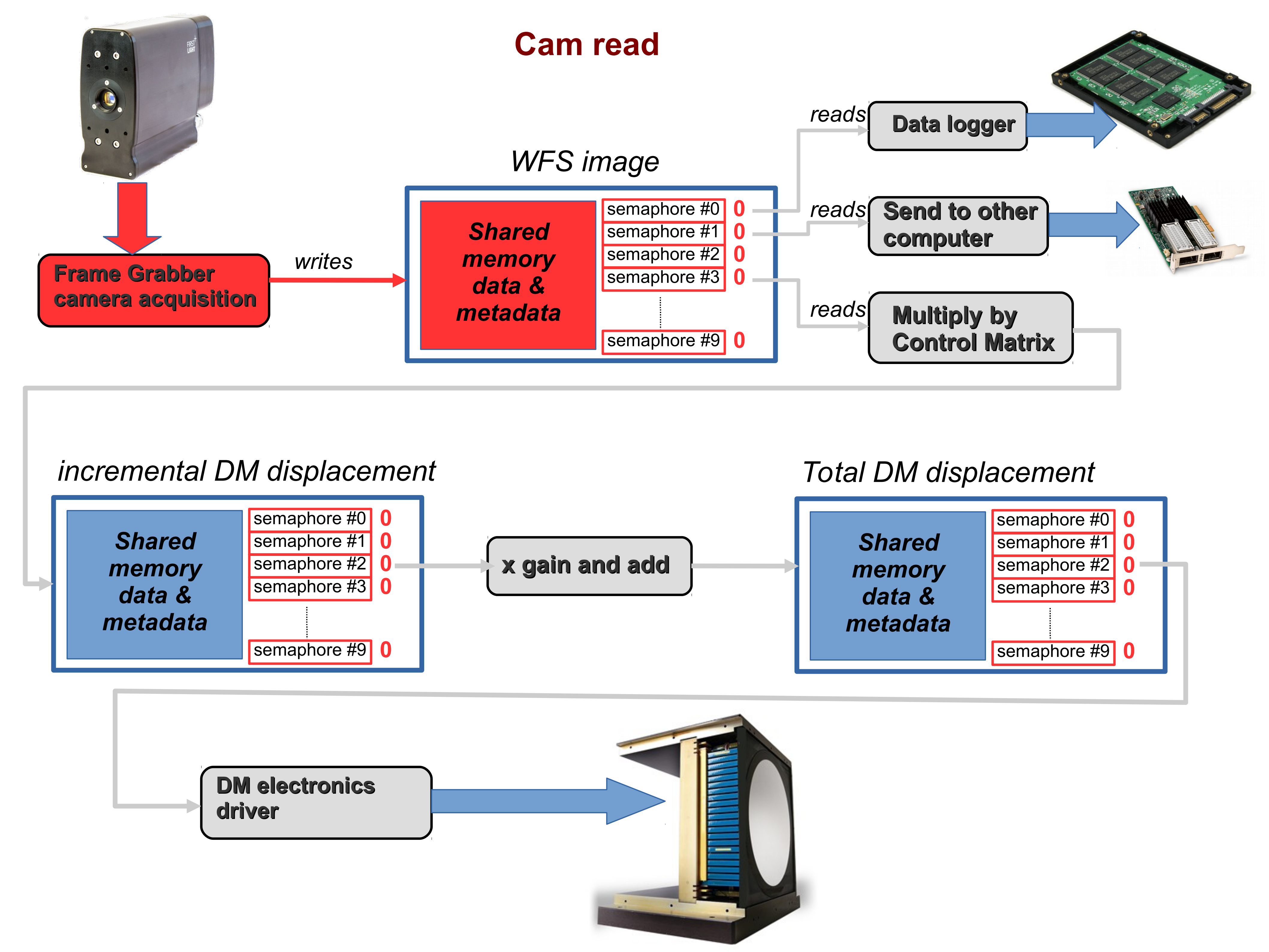
Interprocess communication (IPC) is contained in data: cacao streams are held in shared memory and contain semaphores
→ Complexities of IPC are handled by compiler and Kernel (semaphores, shared memory)



Semaphore-based IPC has us-level latency

A simple example




Cam read
Frame Grabber camera acquisition
writes
WFS image
Shared memory data & metadata
semaphore #0 0
semaphore #1 0
semaphore #2 0
semaphore #3 0
semaphore #9 0
reads
Data logger
reads
Send to other computer
reads
Multiply by Control Matrix
incremental DM displacement
Shared memory data & metadata
semaphore #0 0
semaphore #1 0
semaphore #2 0
semaphore #3 0
semaphore #9 0
x gain and add
Total DM displacement
Shared memory data & metadata
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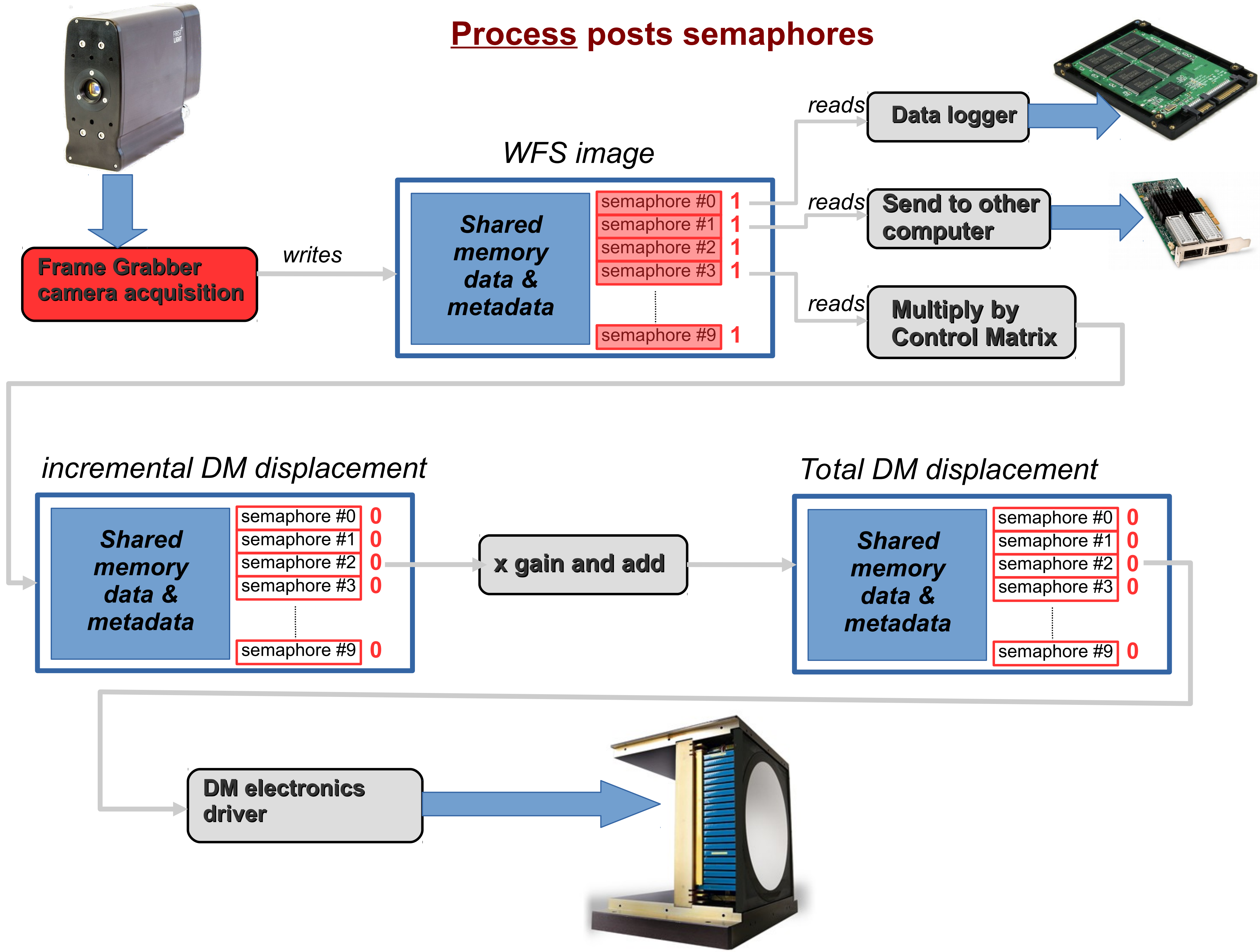
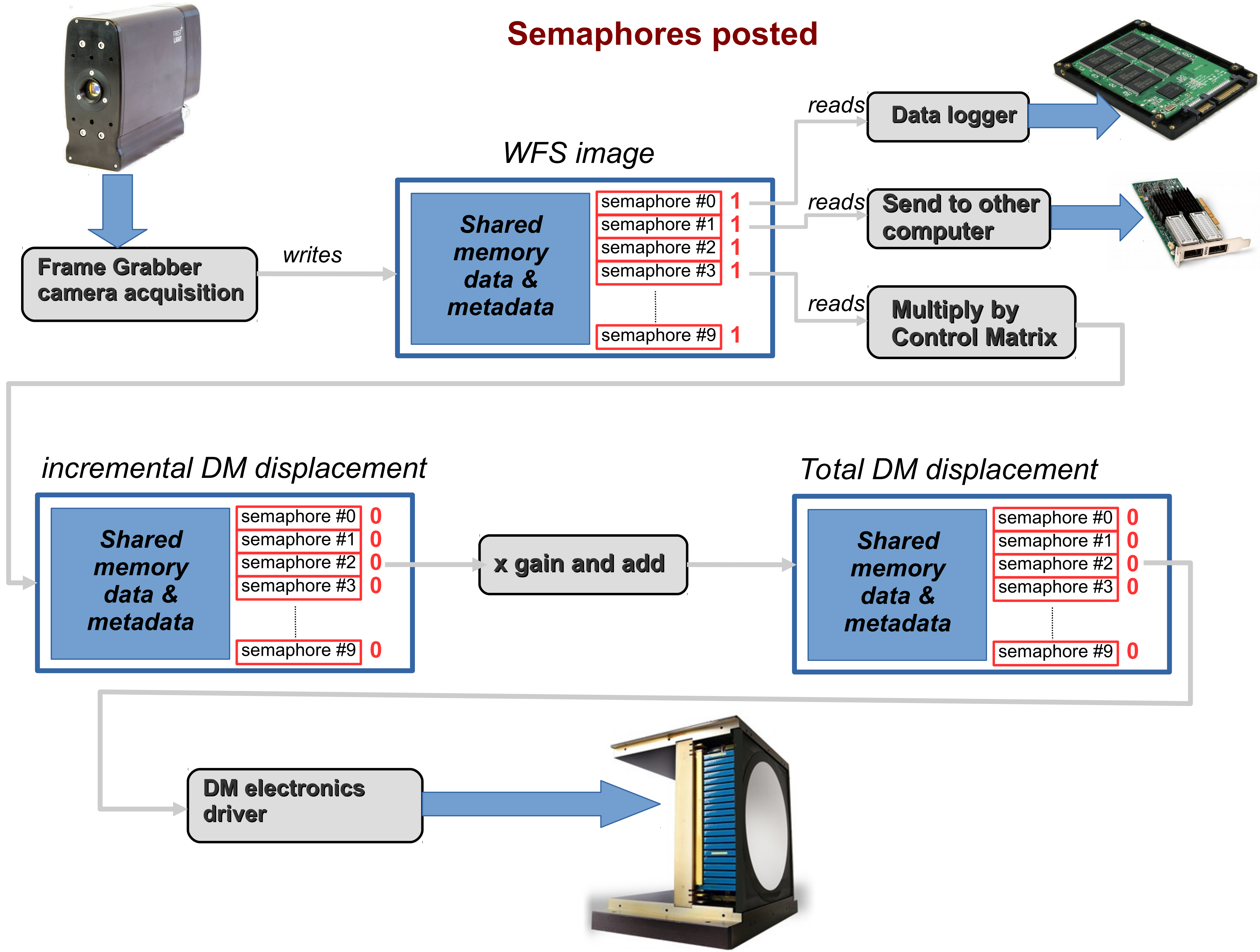
DM electronics driver

Process posts semaphores




Semaphores posted
WFS image
Frame Grabber camera acquisition
writes
Shared memory data & metadata
semaphore #0 1
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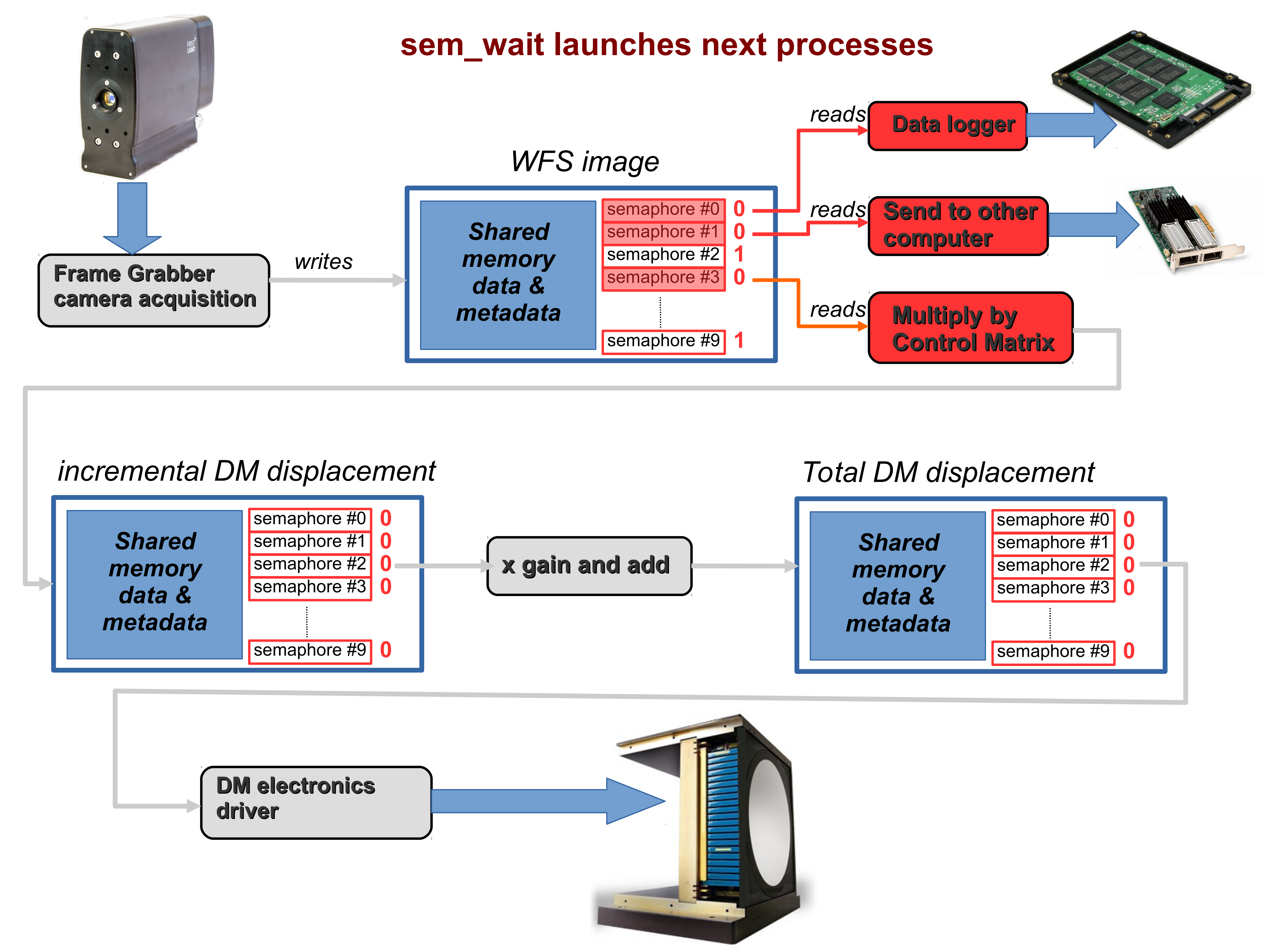
sem_wait launches next processes
Frame Grabber camera acquisition
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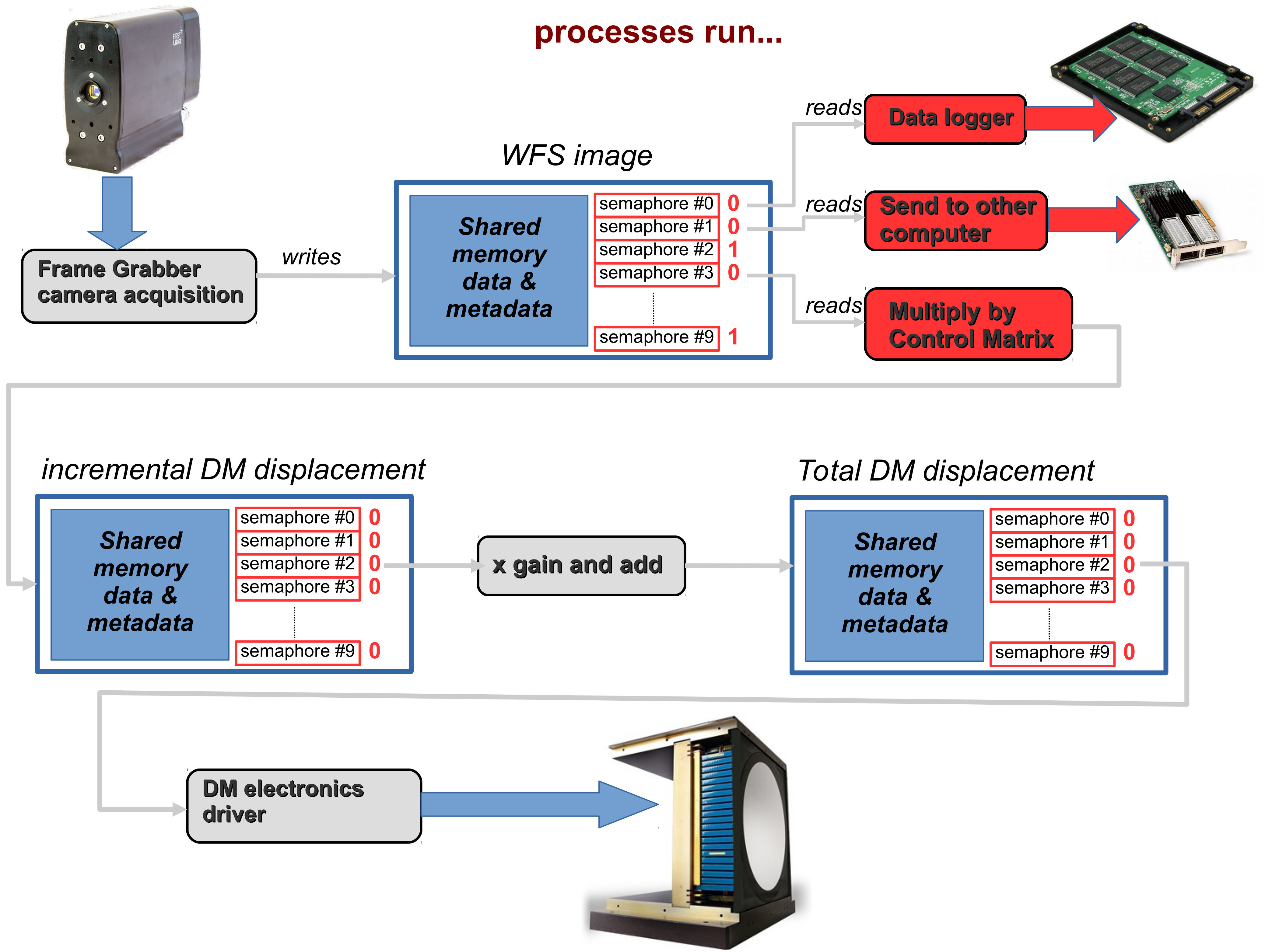
processes run...
Frame Grabber camera acquisition
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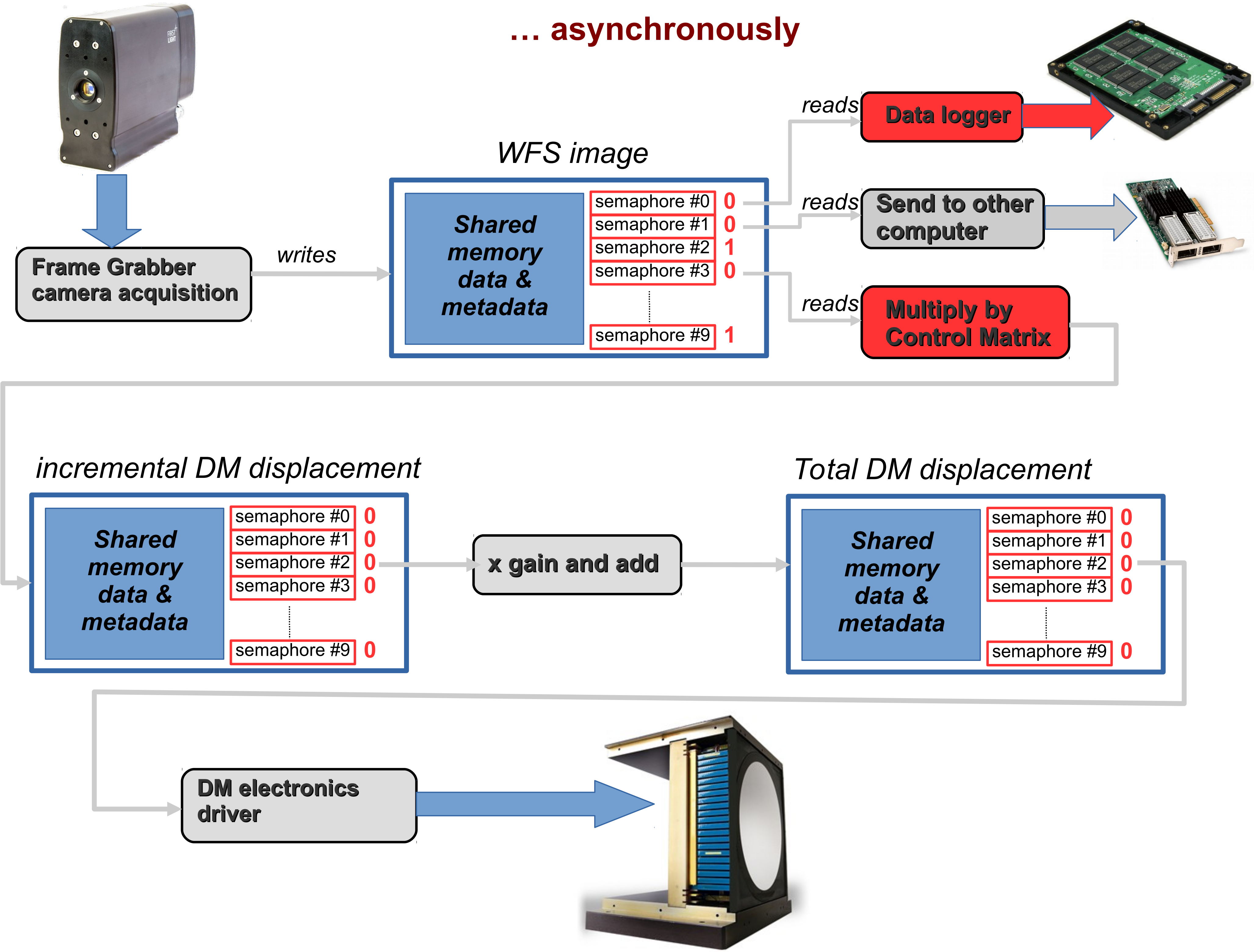

… asynchronously
Frame Grabber camera acquisition
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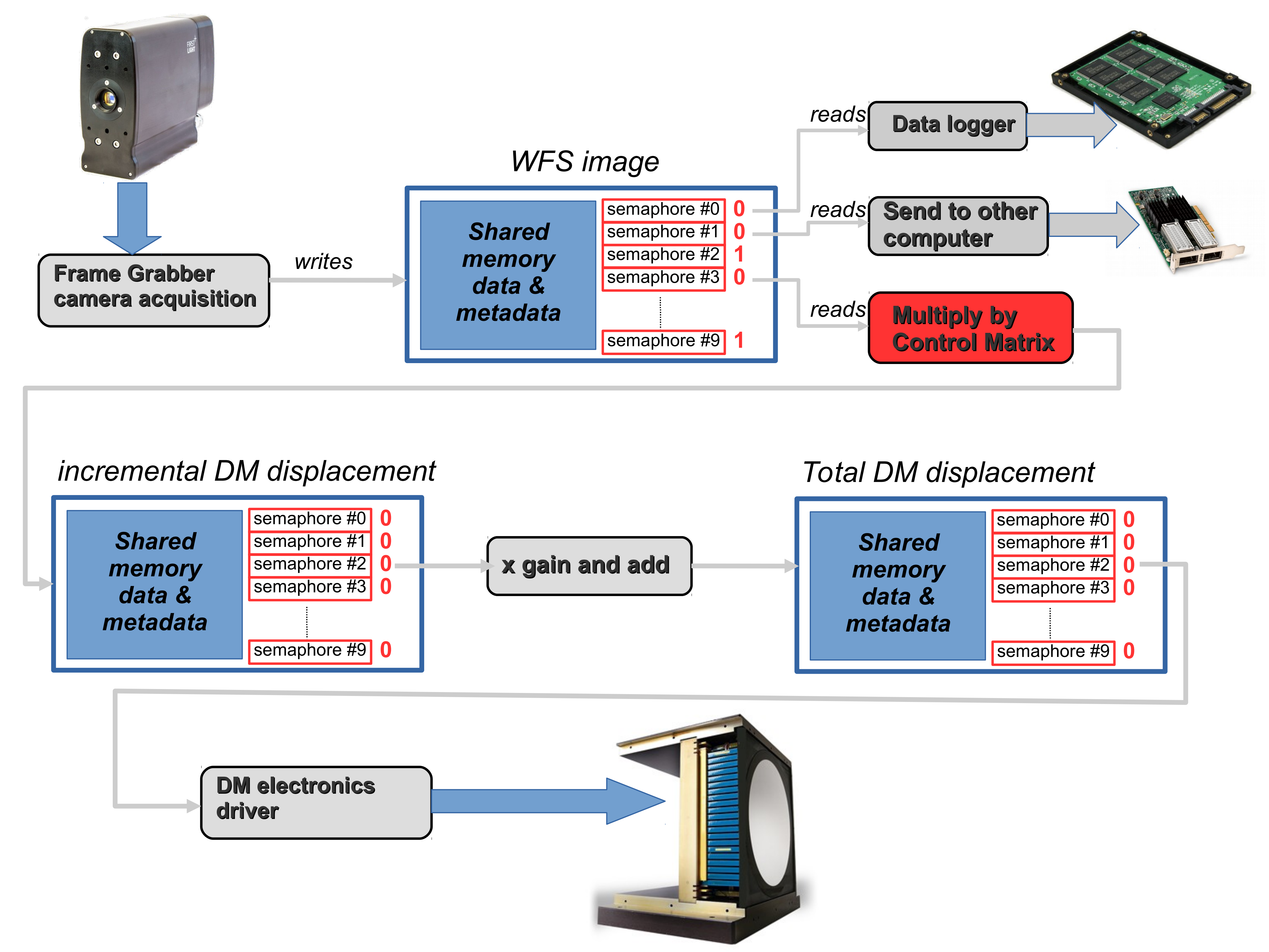

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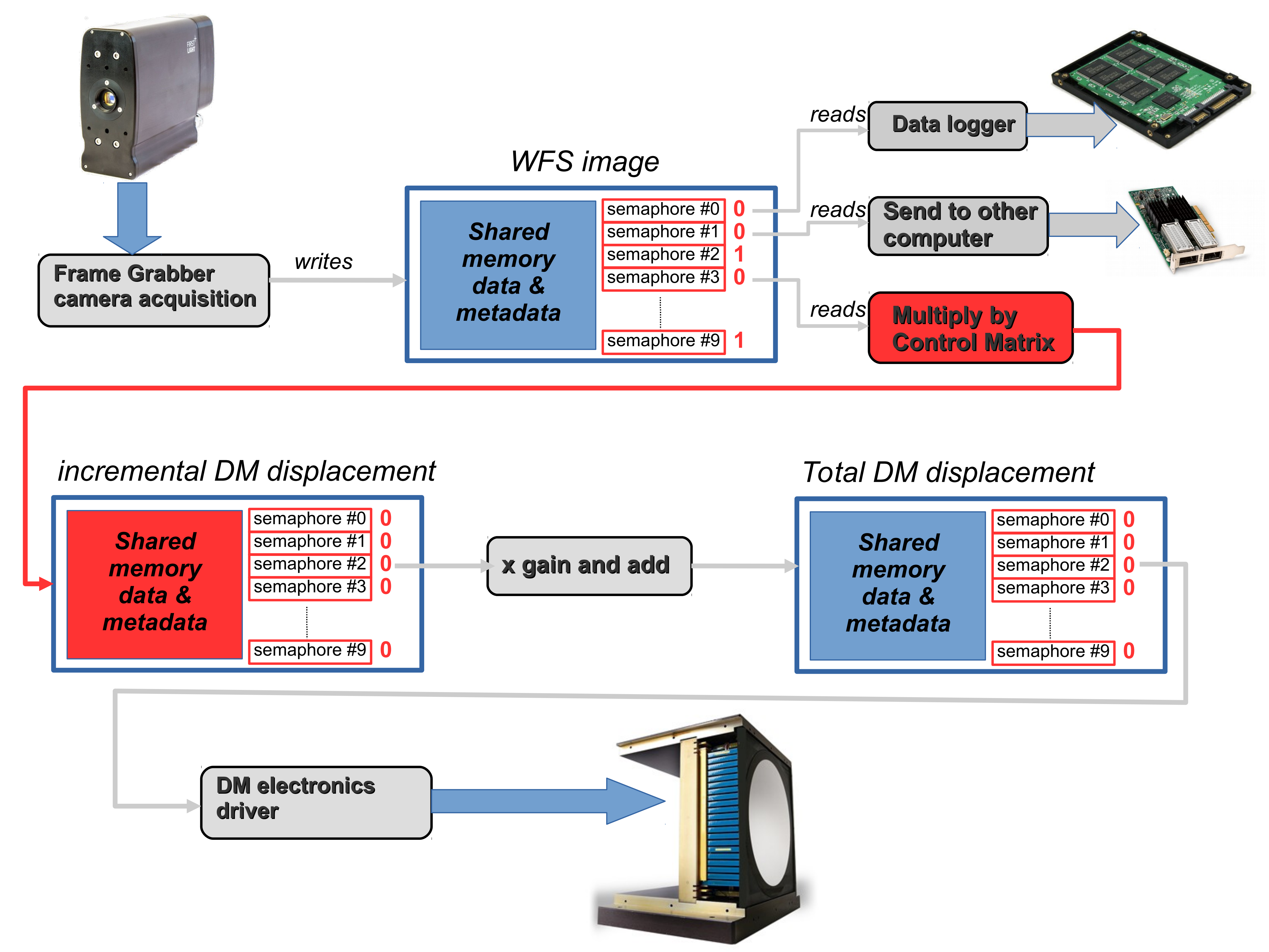

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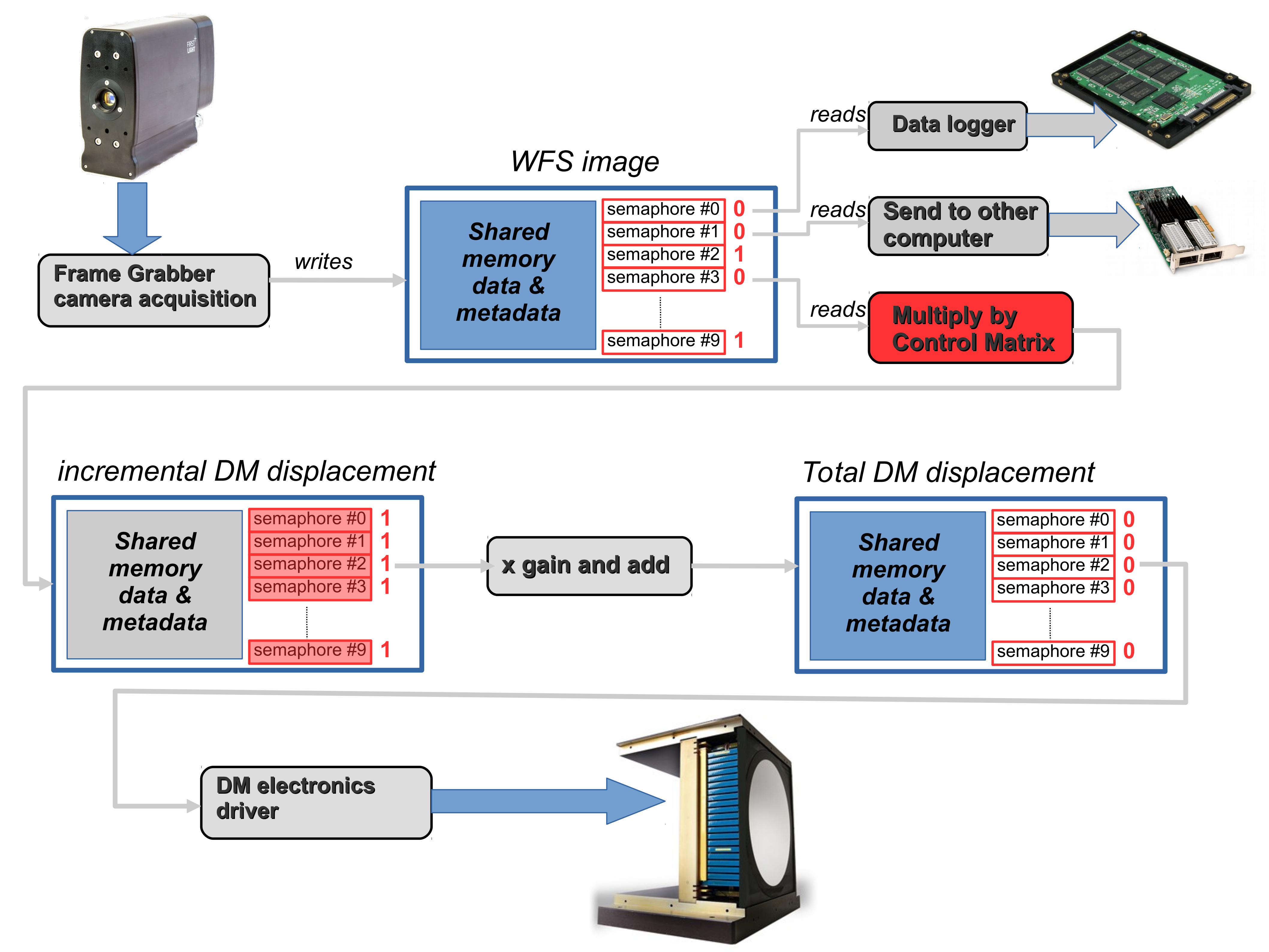

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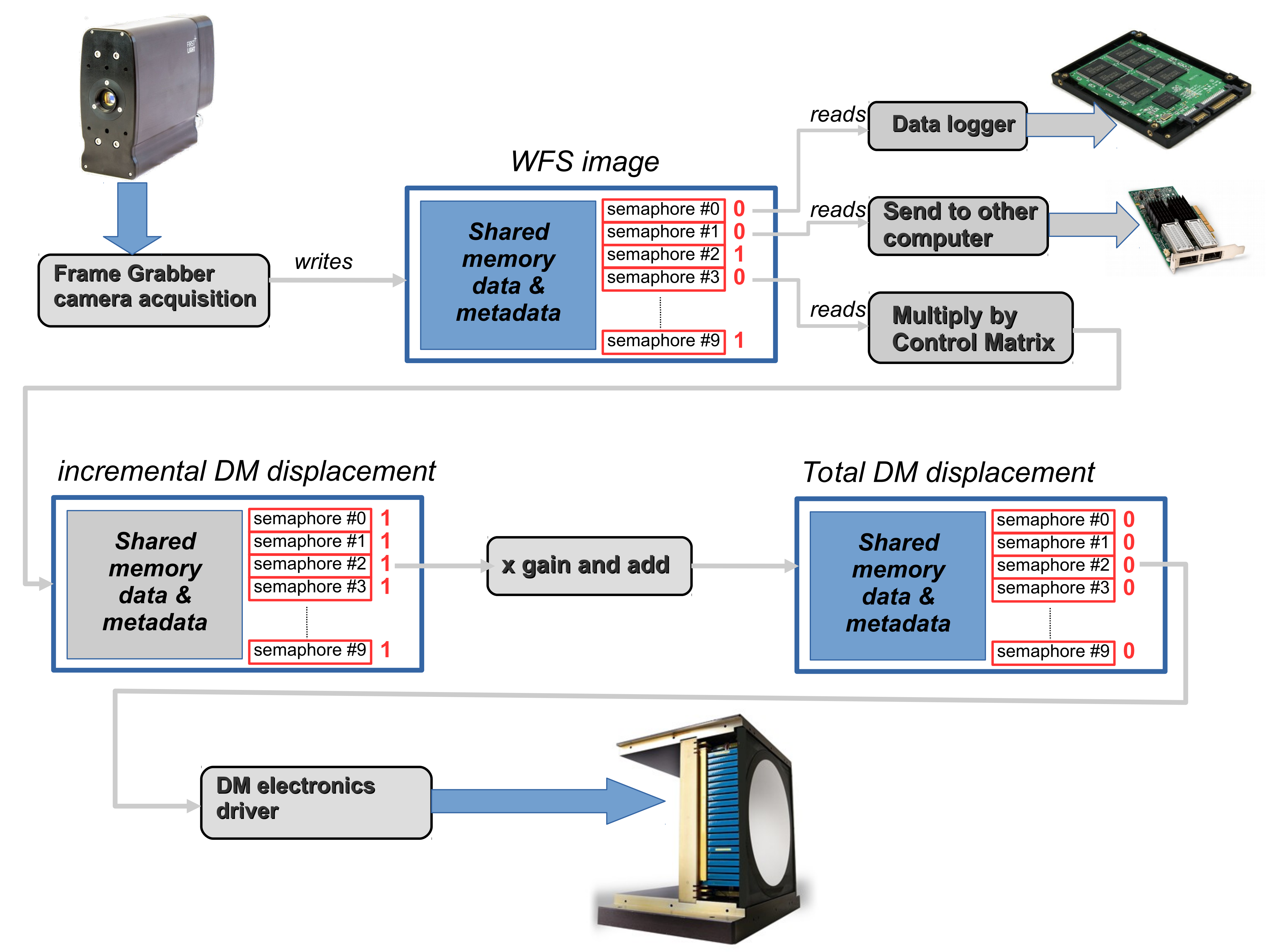

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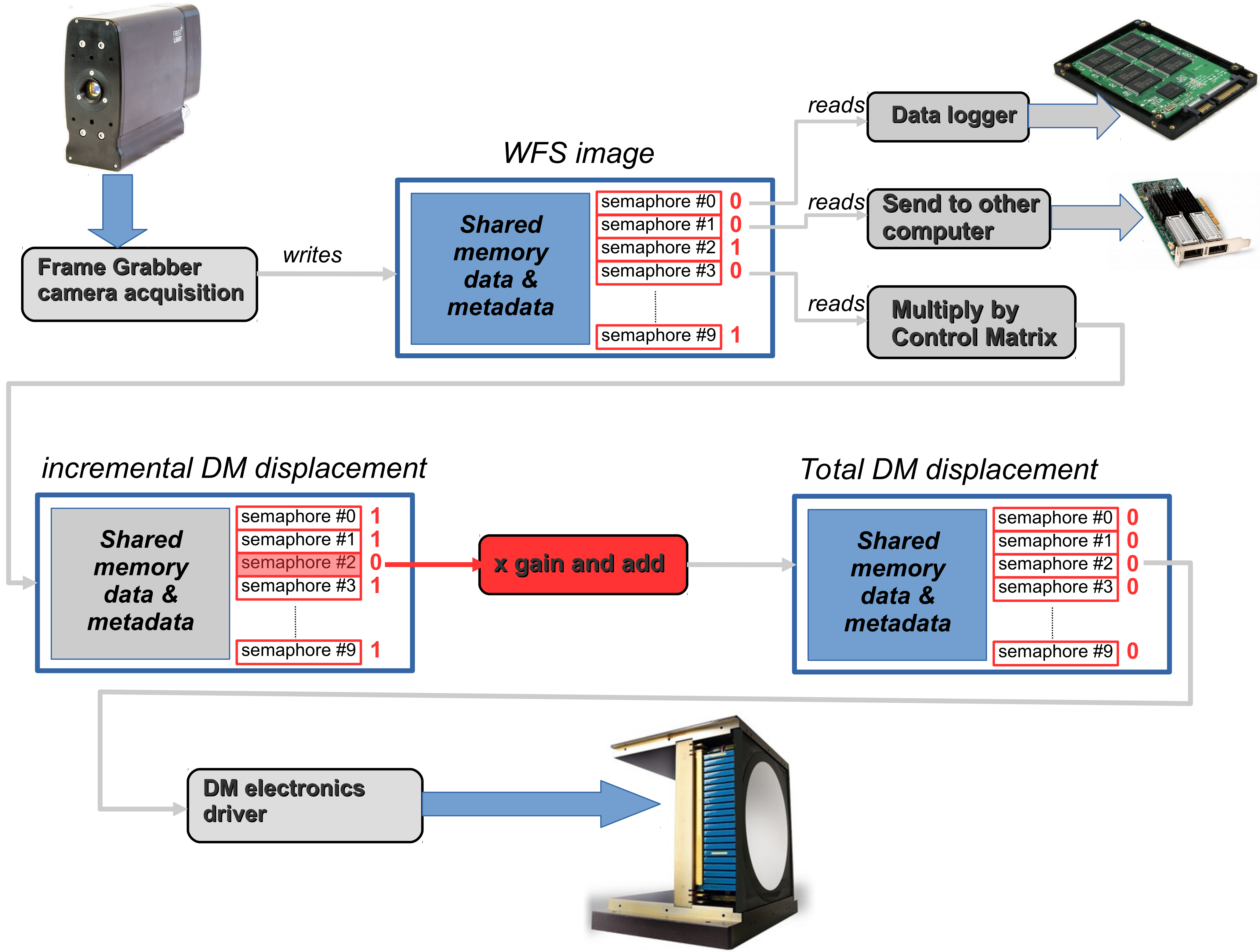

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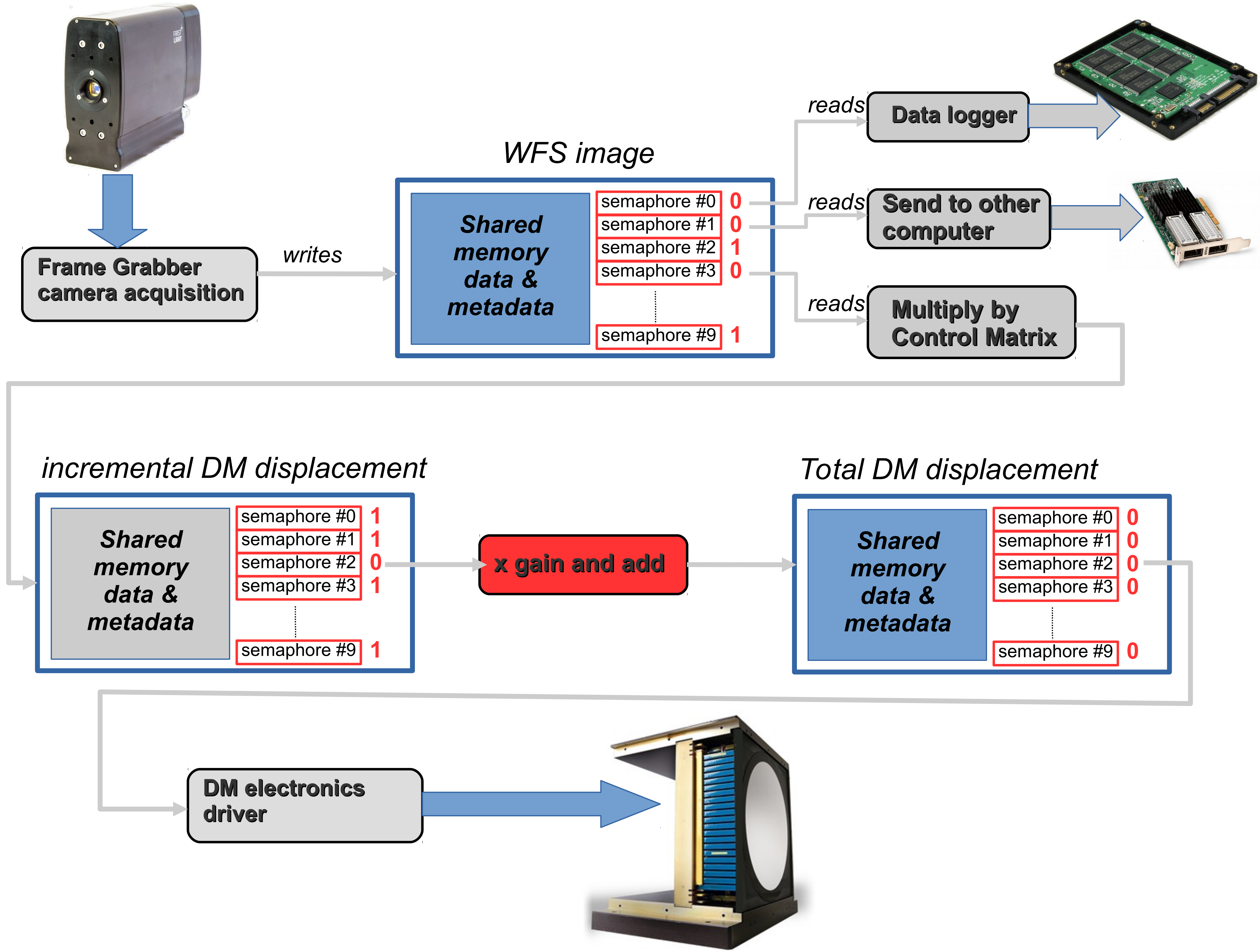

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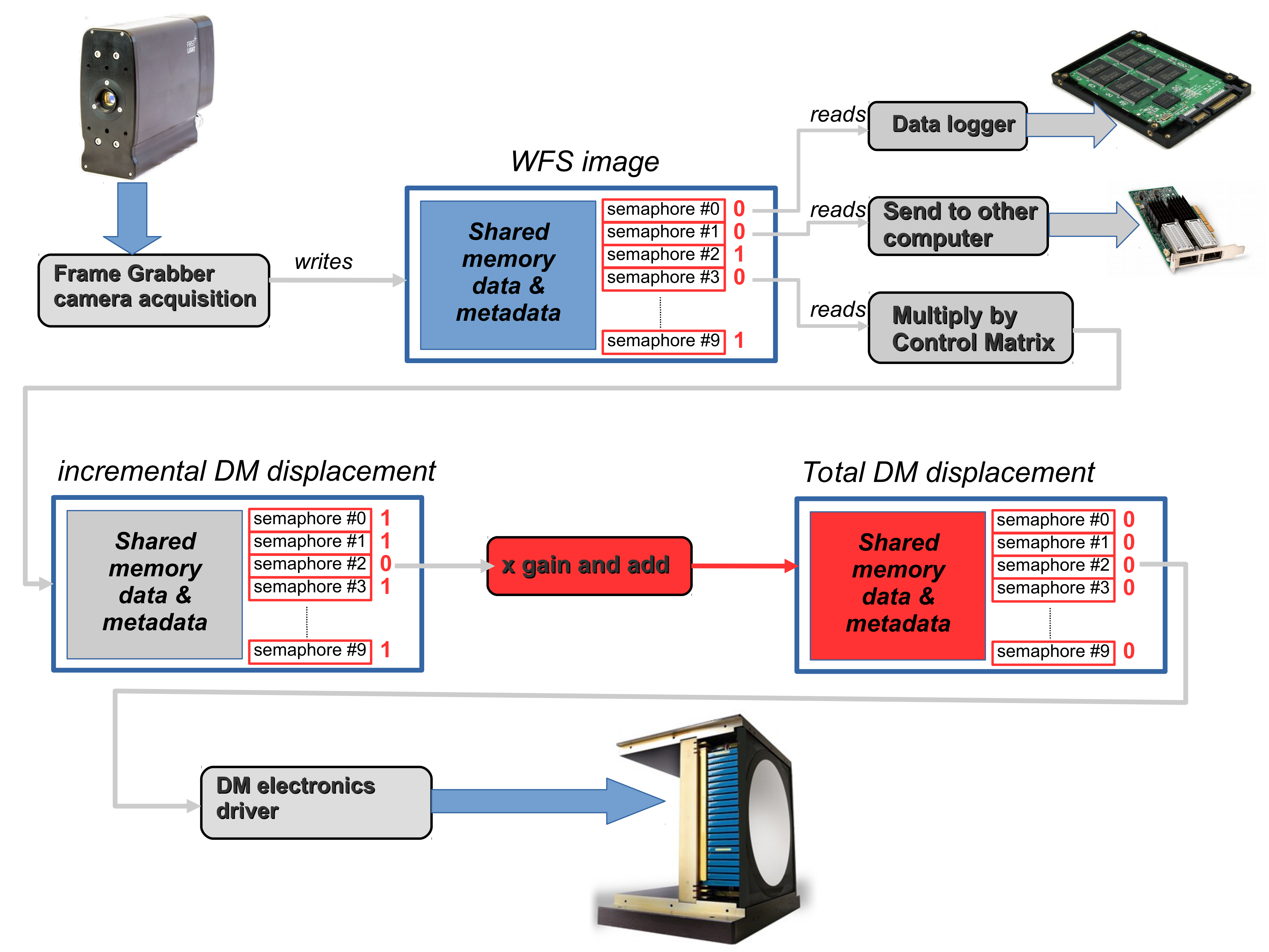
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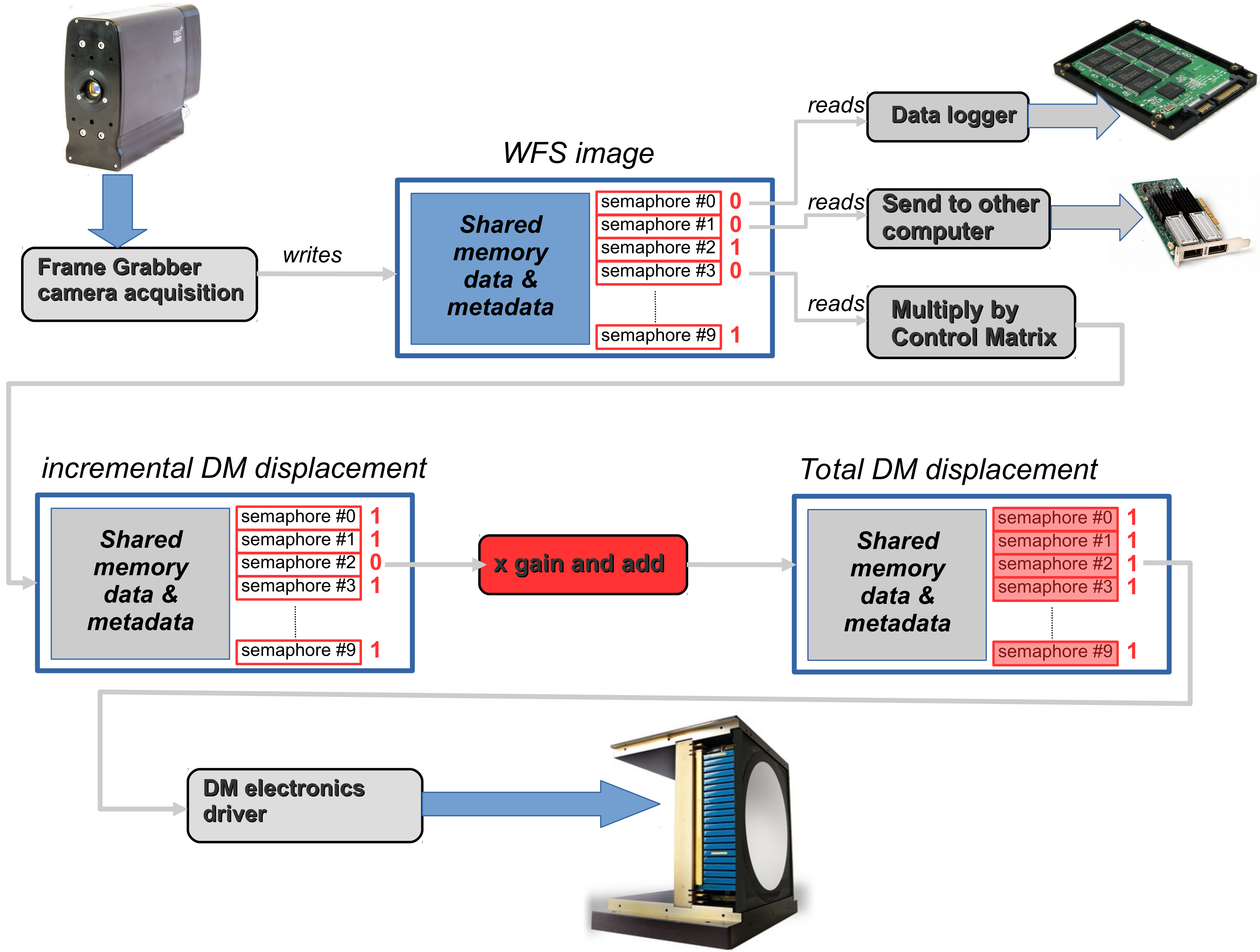

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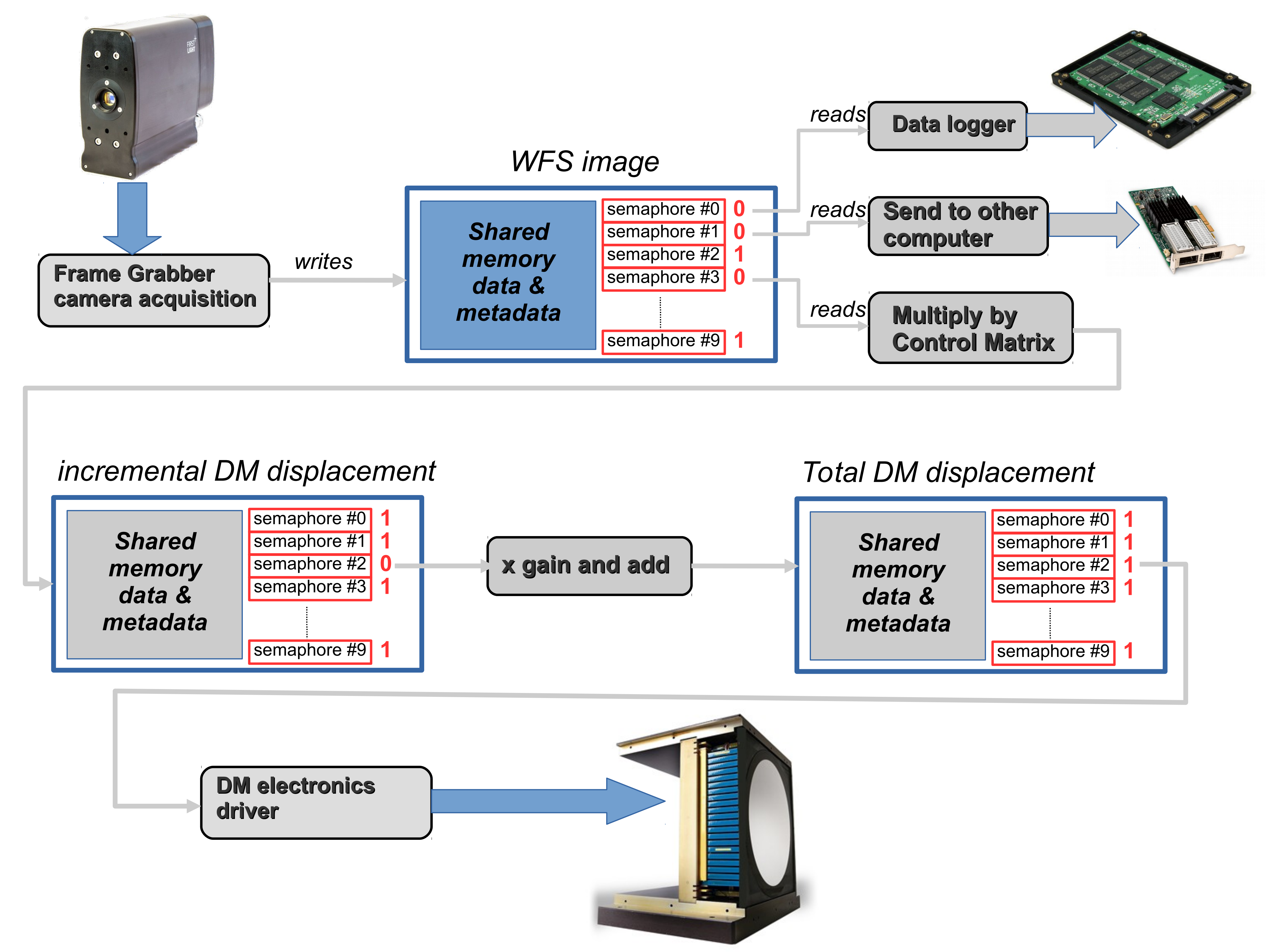

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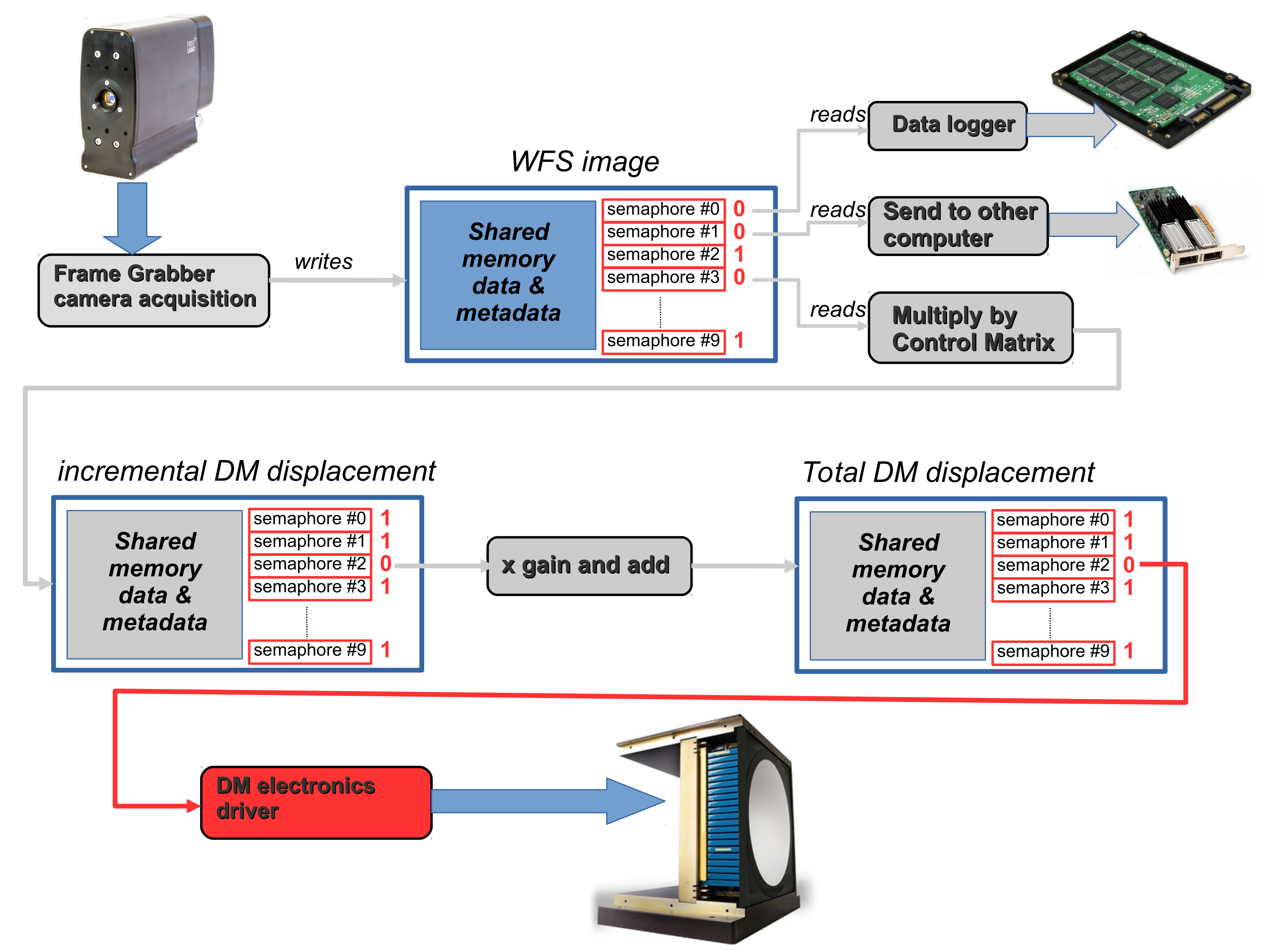

WFS image
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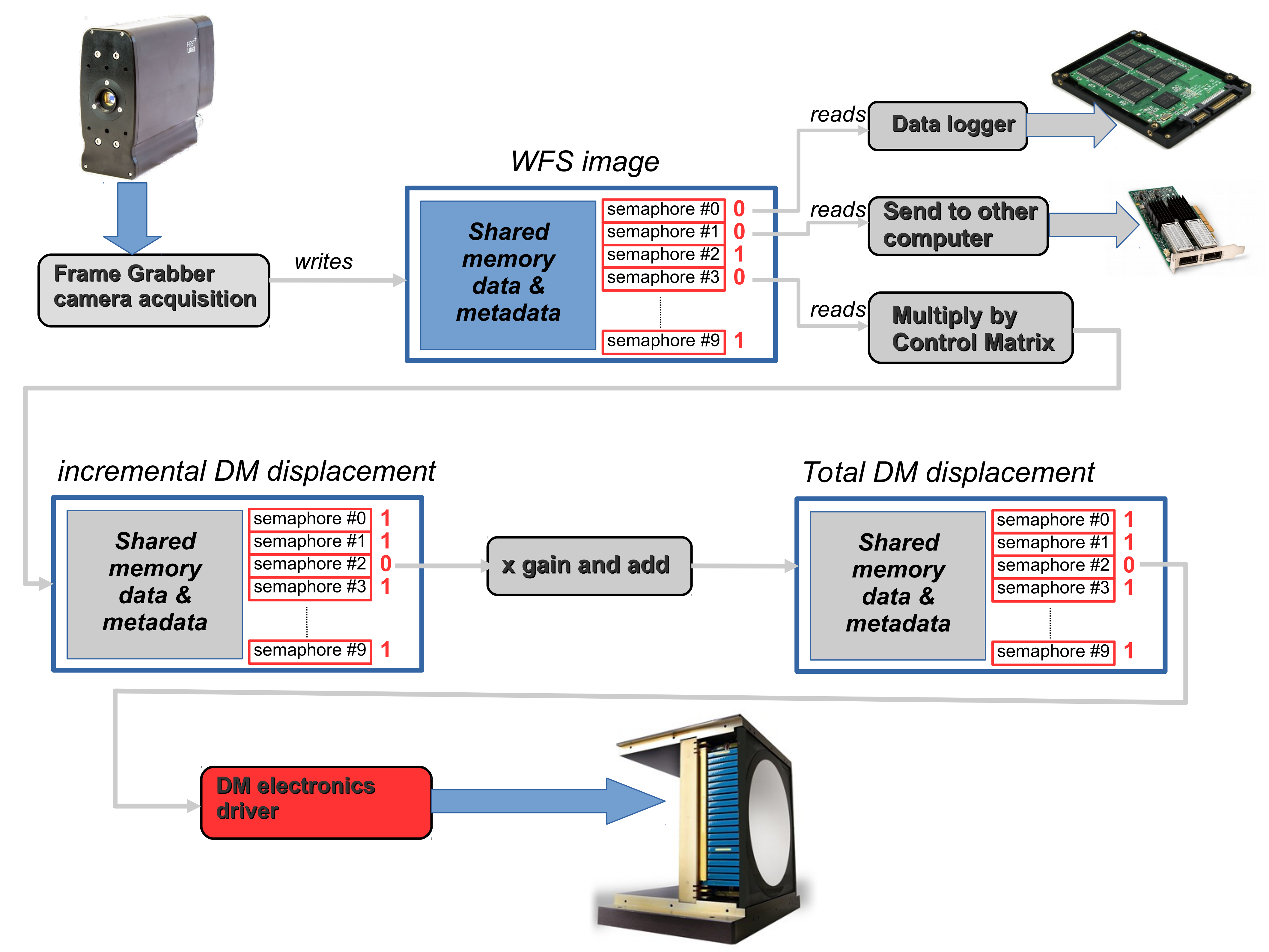

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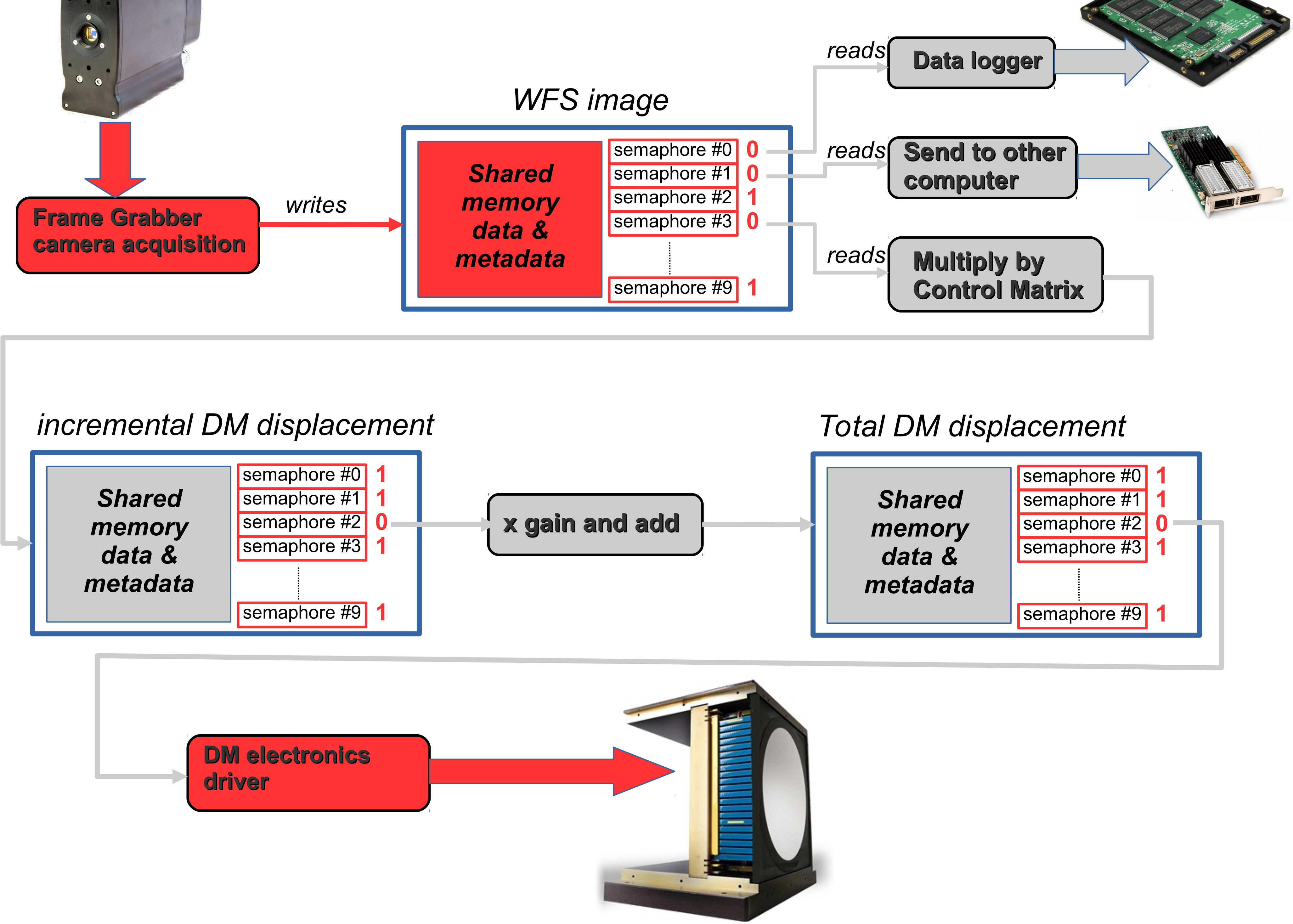
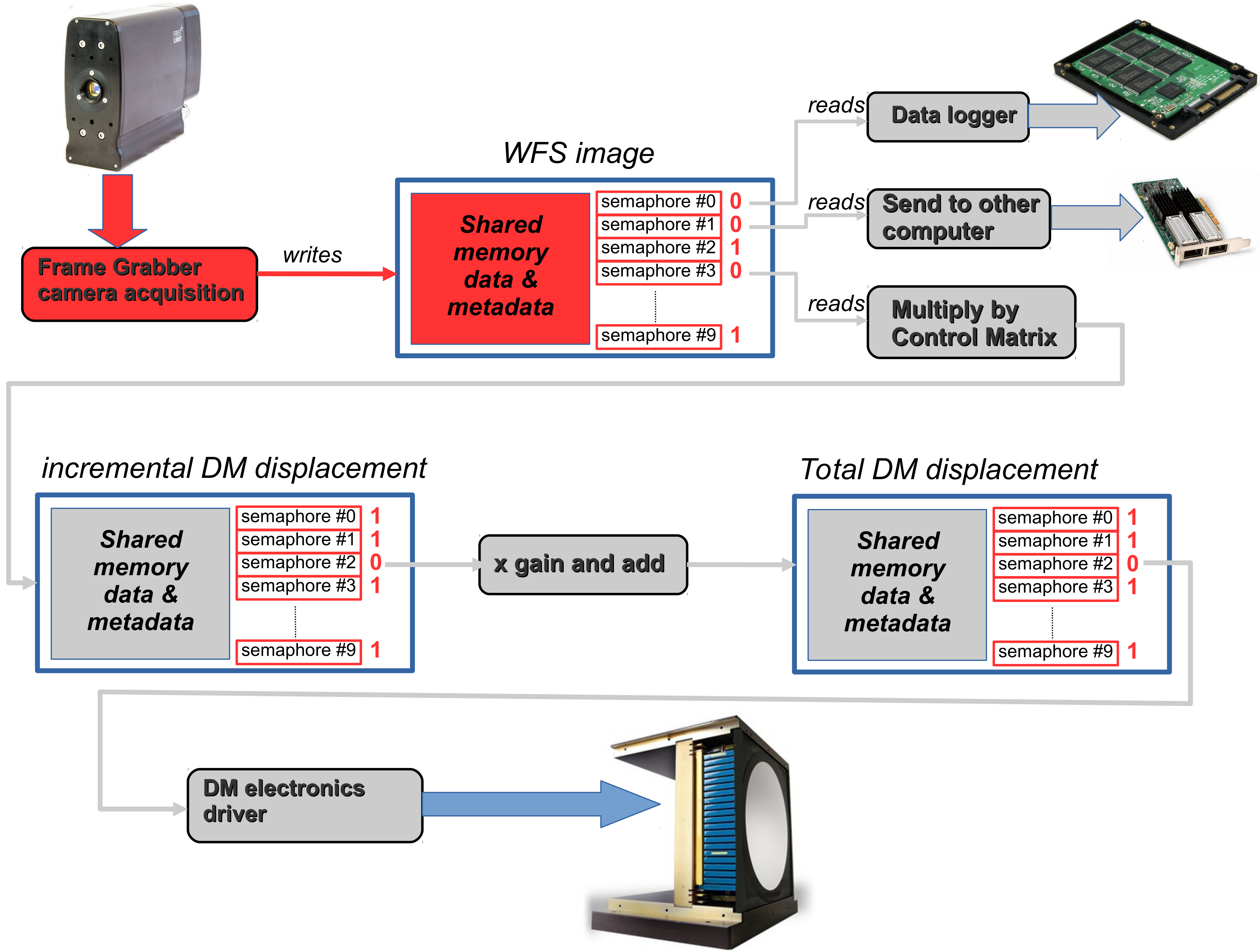
DM electronics driver

processes execution can overlap

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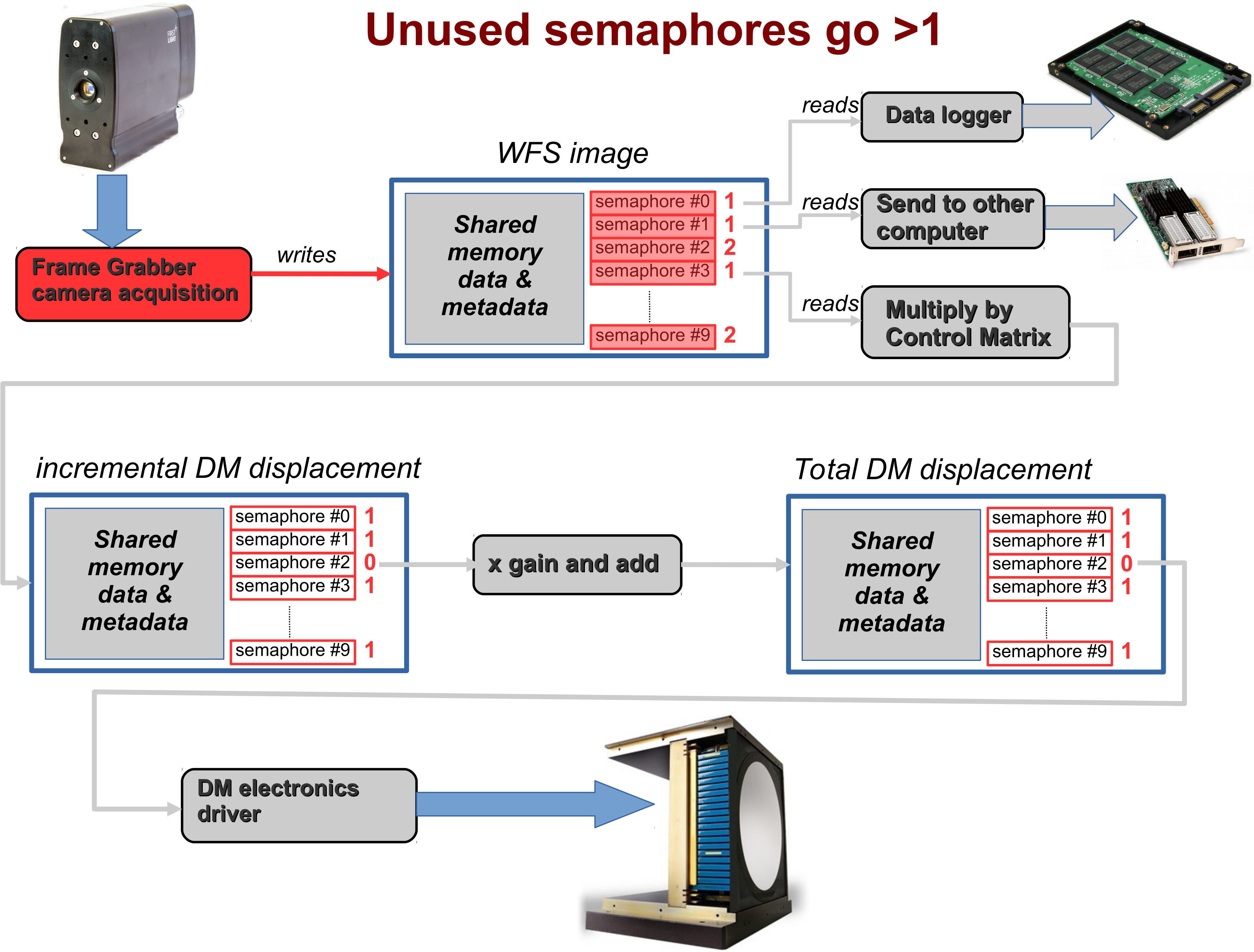
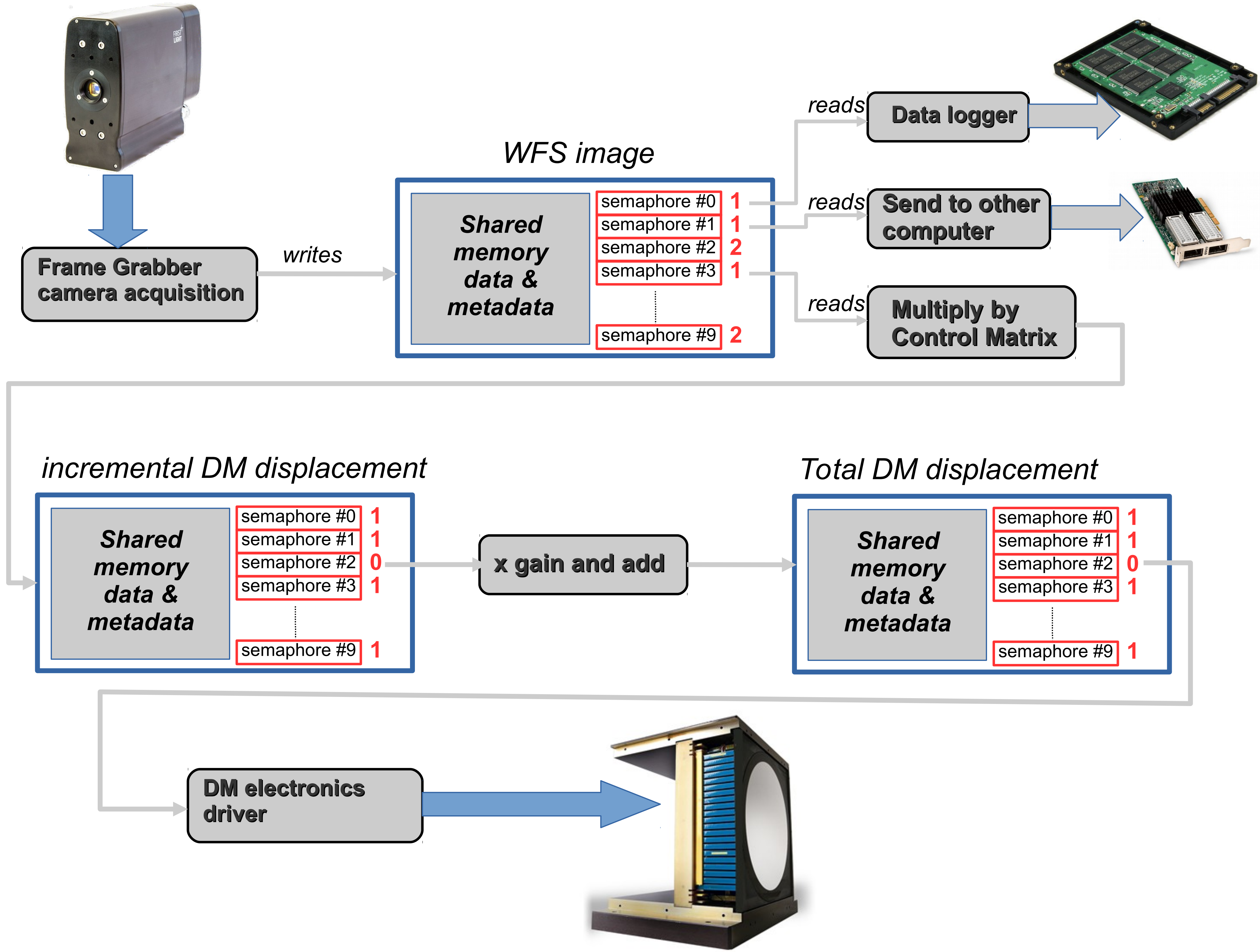
DM electronics driver

Unused semaphores go >1





WFS image
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semaphore #0 1
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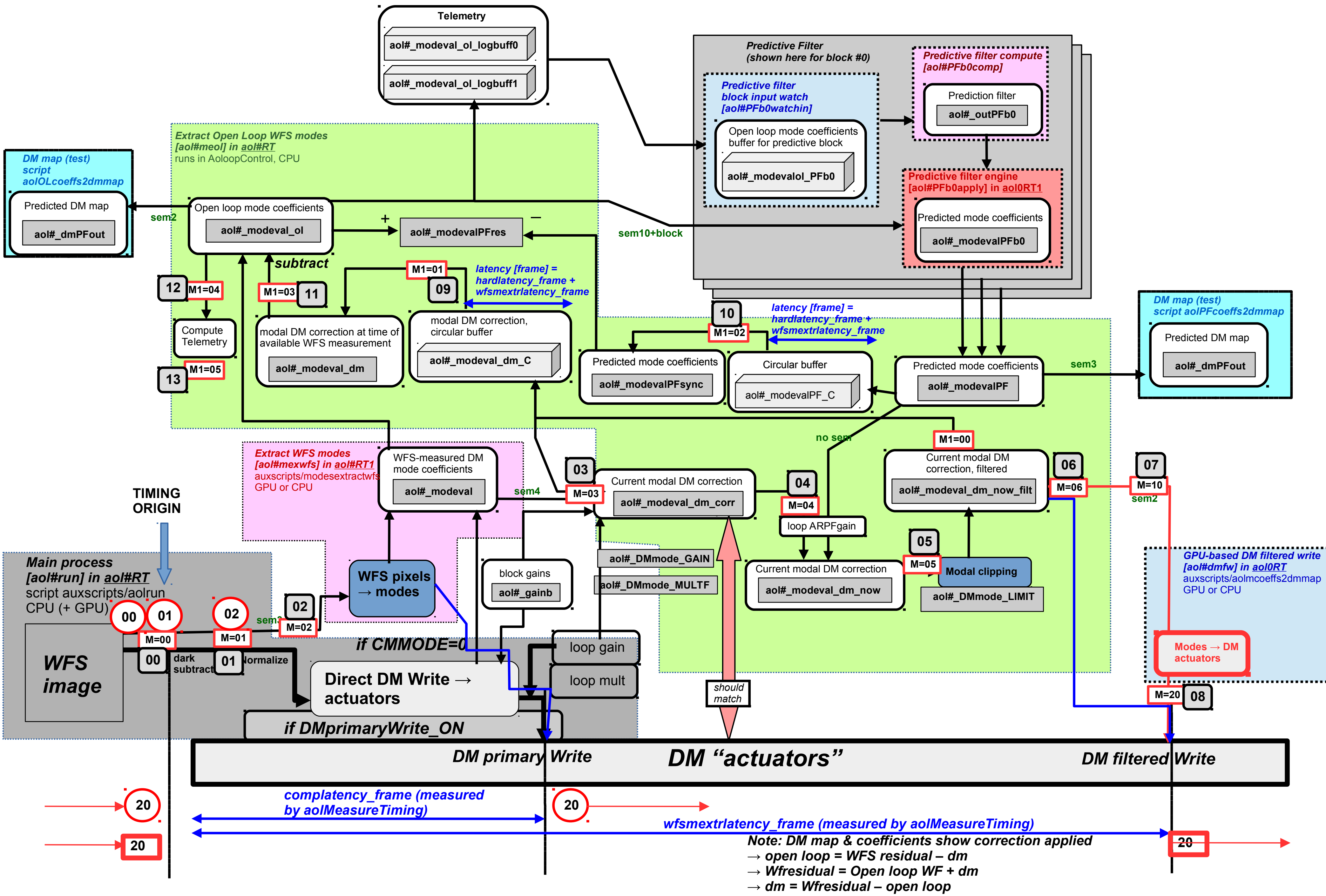
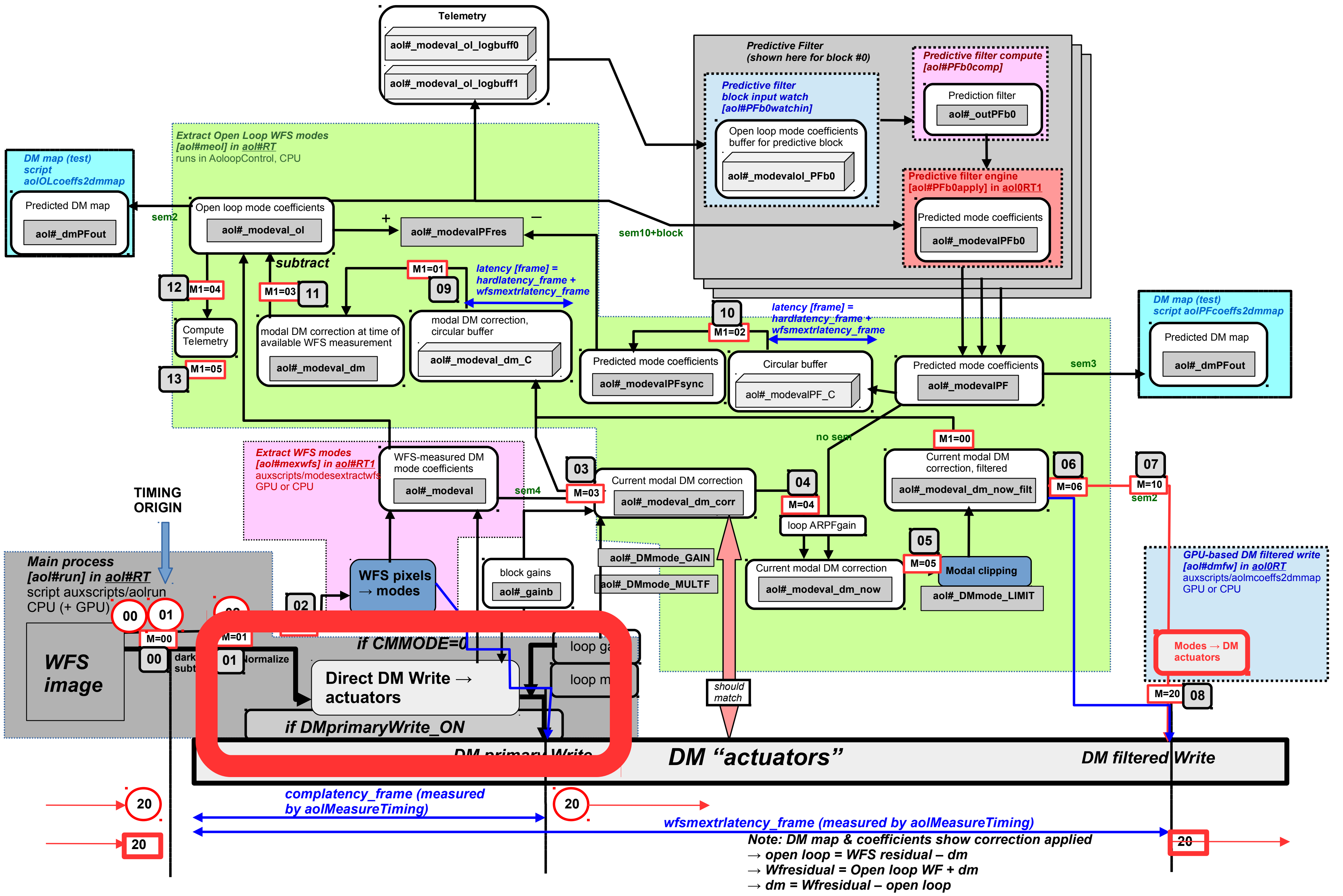
DM electronics driver

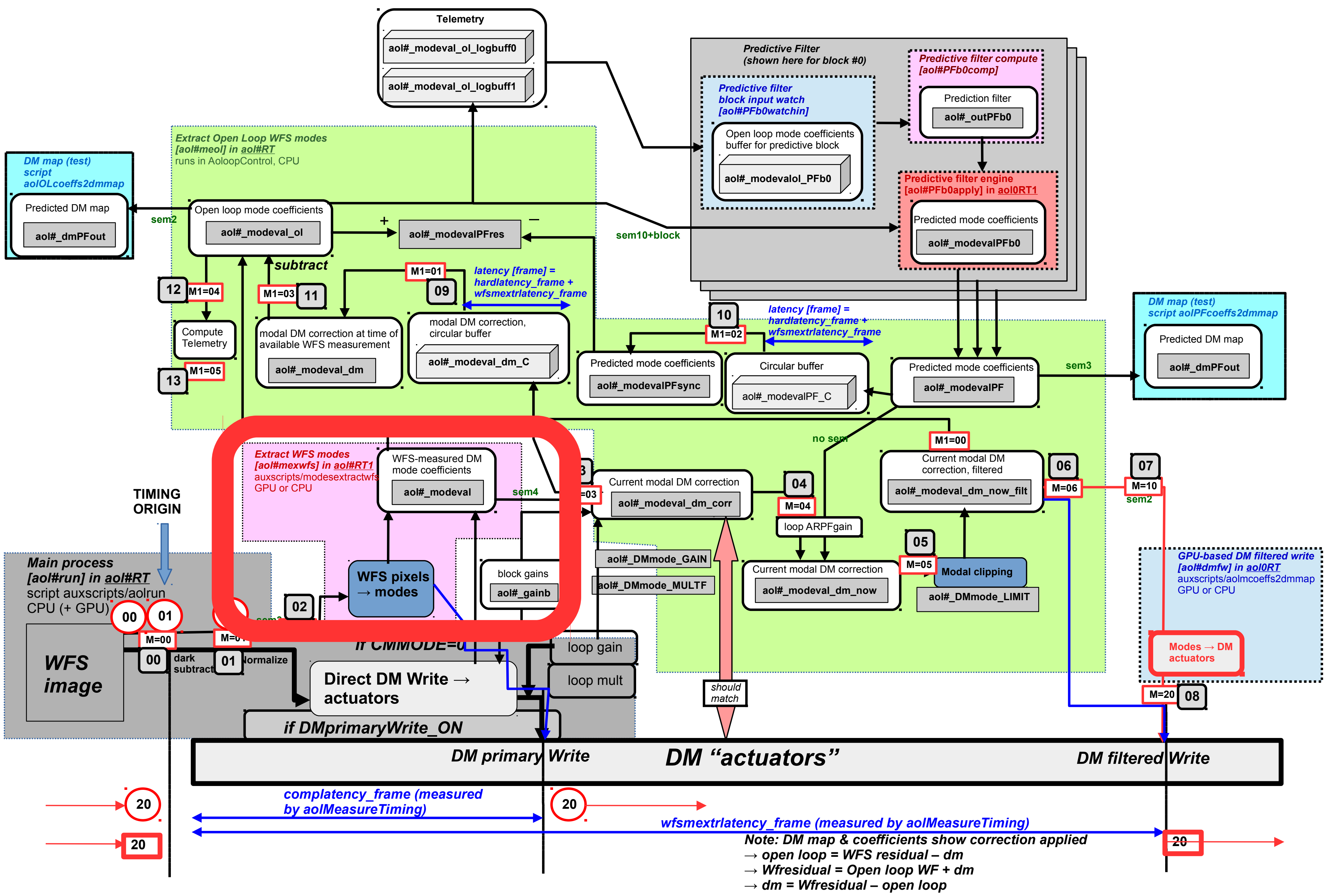
A more powerful example (SCExAO control loop)



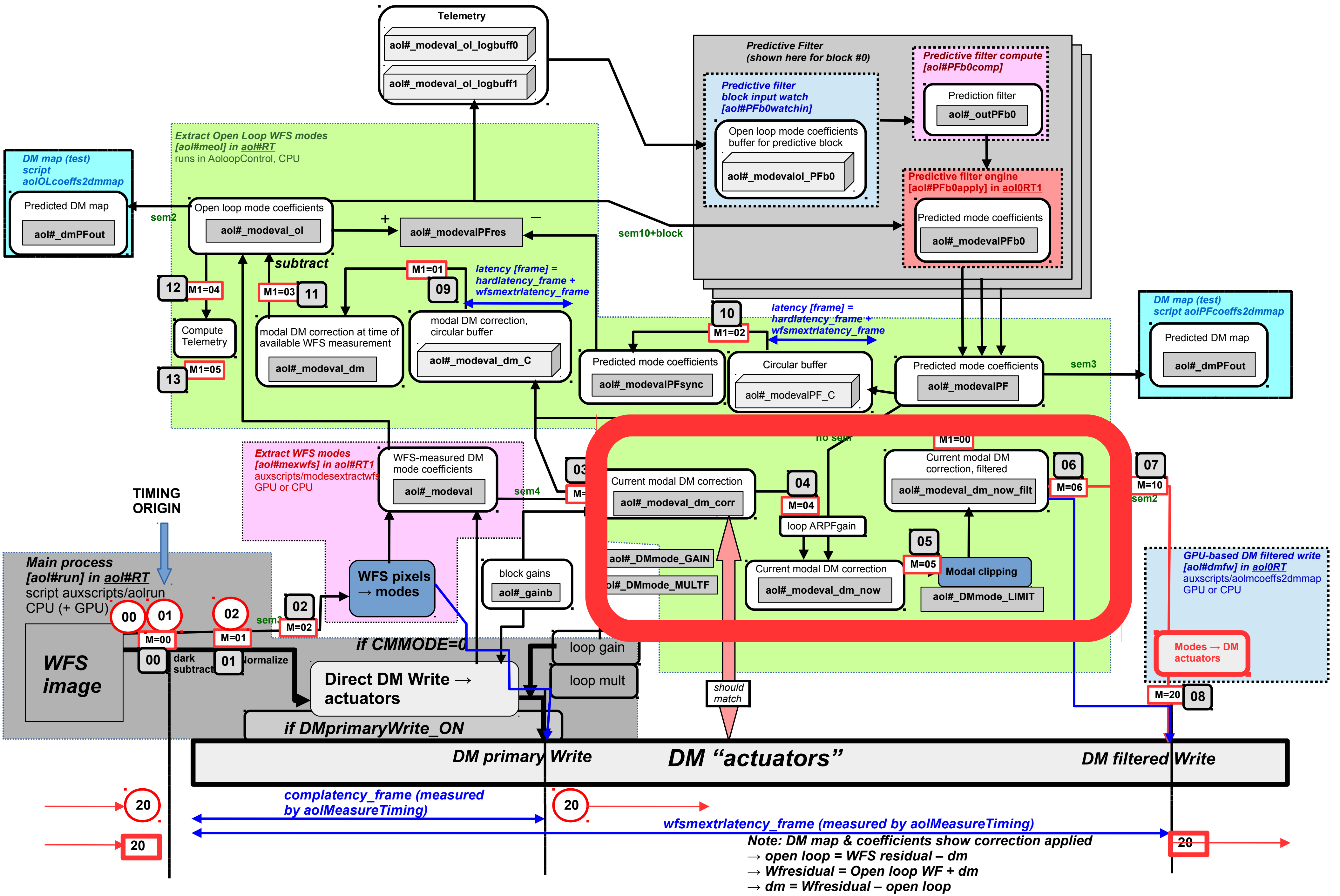
Fastest way to write on DM is to multiply WFS image by control matrix → DM actuators



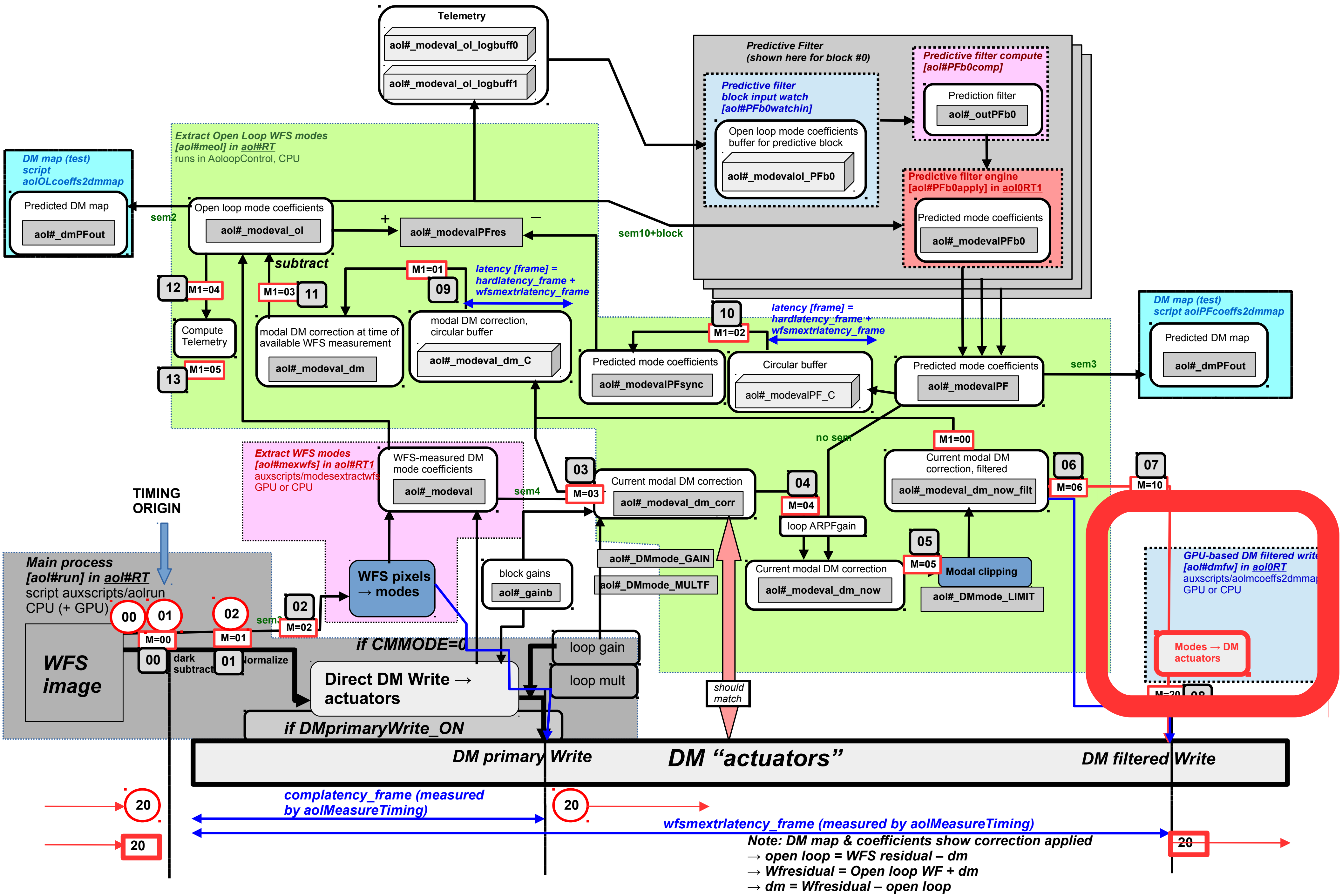
Modal reconstruction: compute WF modes from WFS image (usually GPU-based)



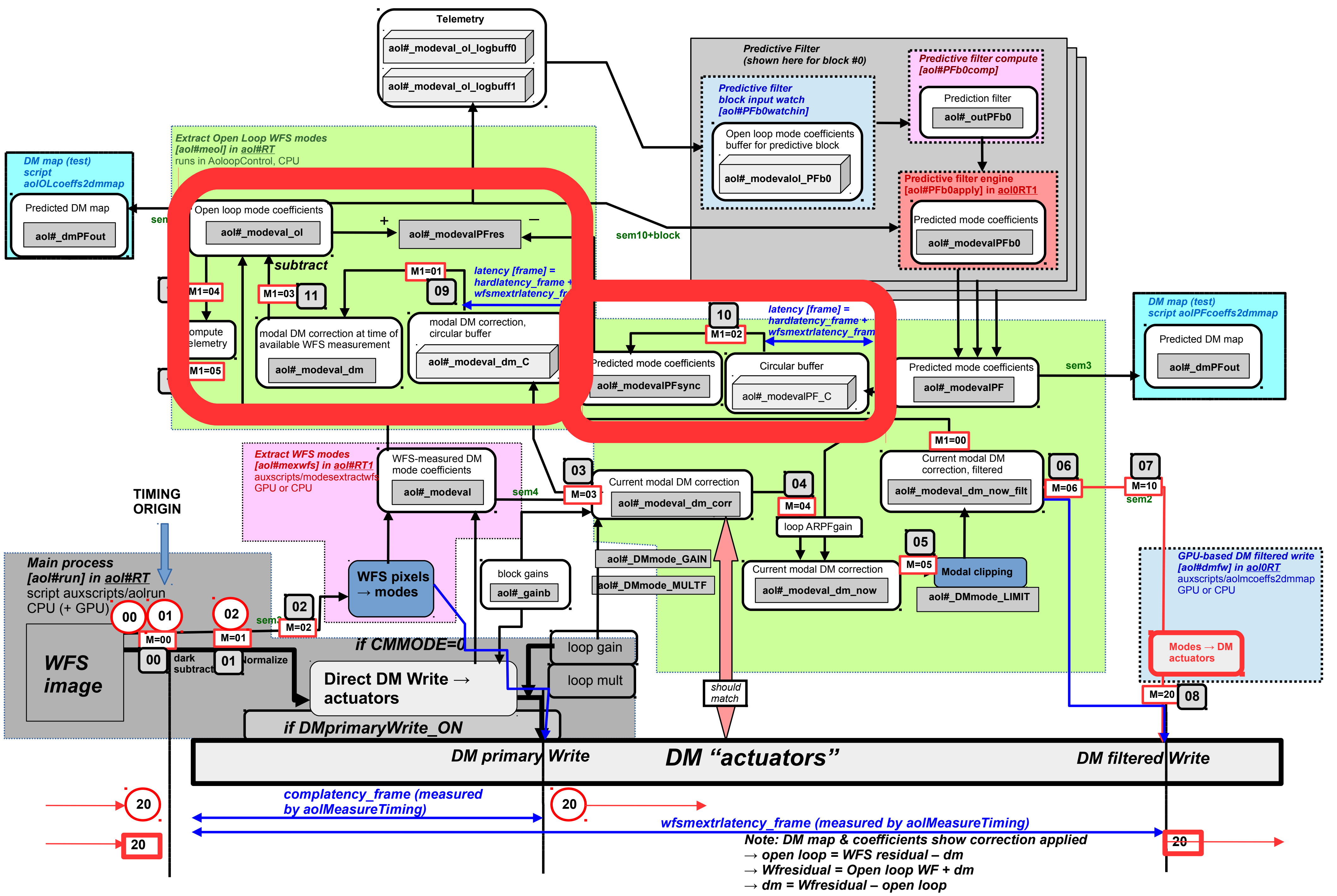
Modal filtering



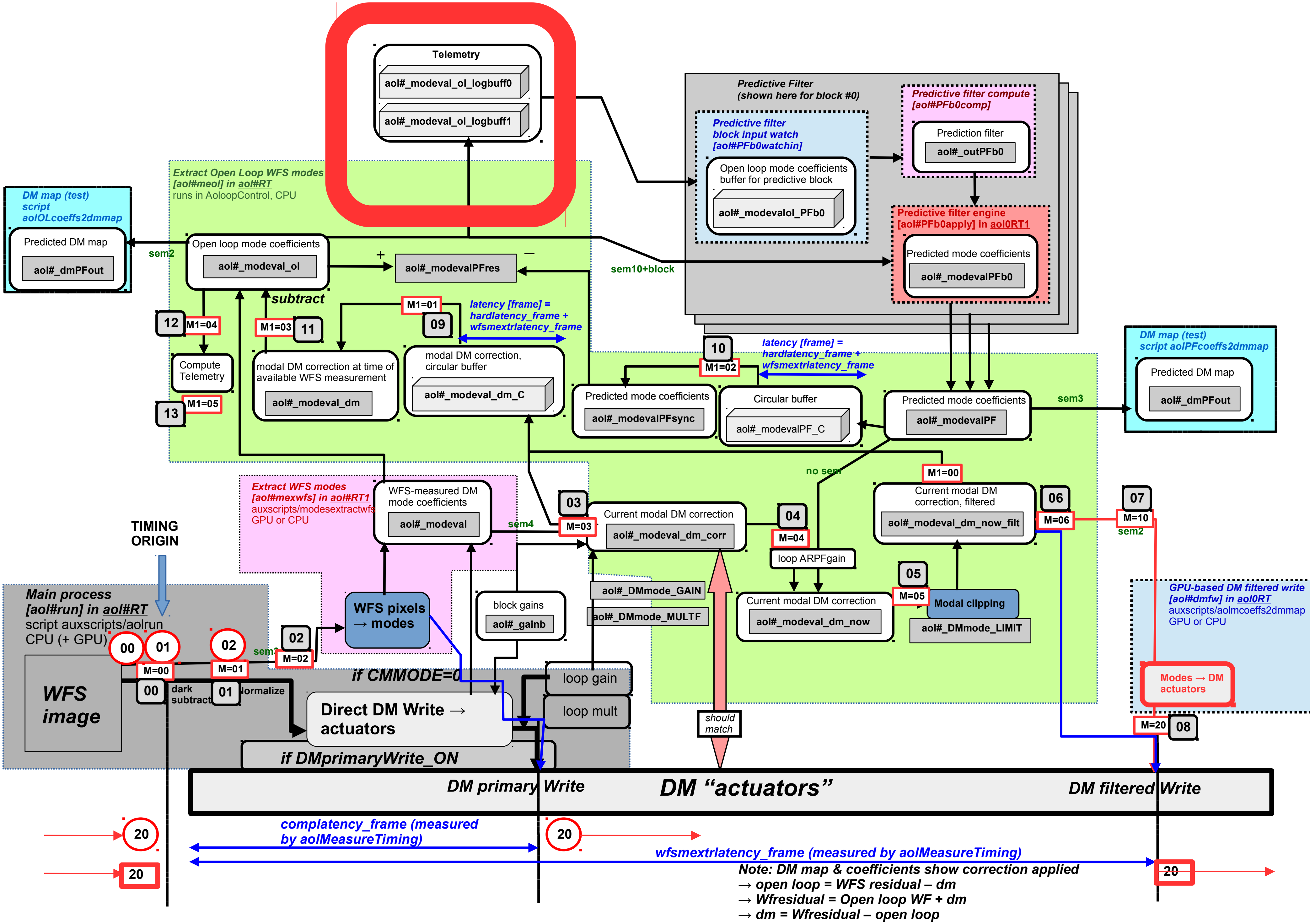
Modes → DM actuators (MVM operation)



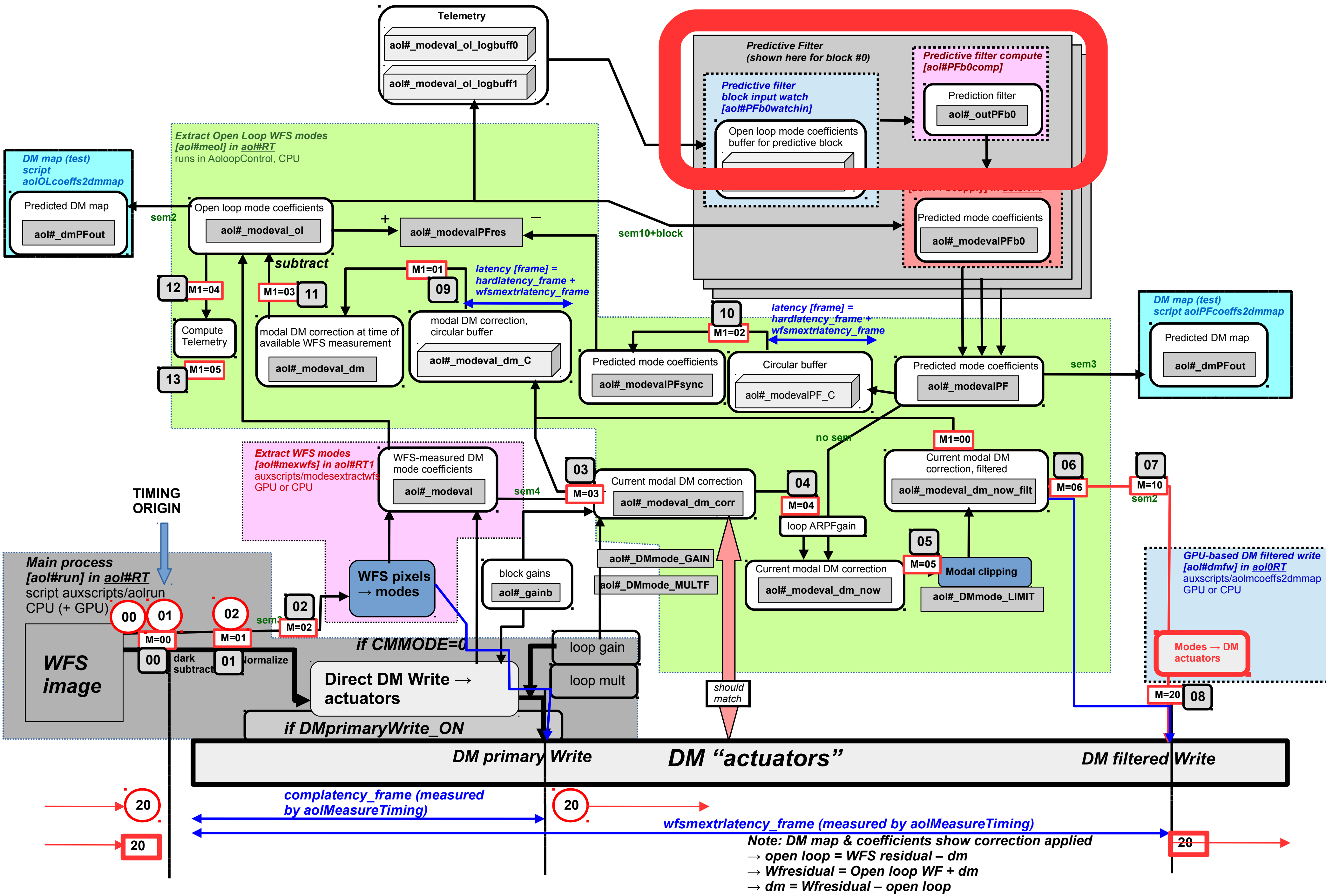
Modal pseudo-open loop reconstruction



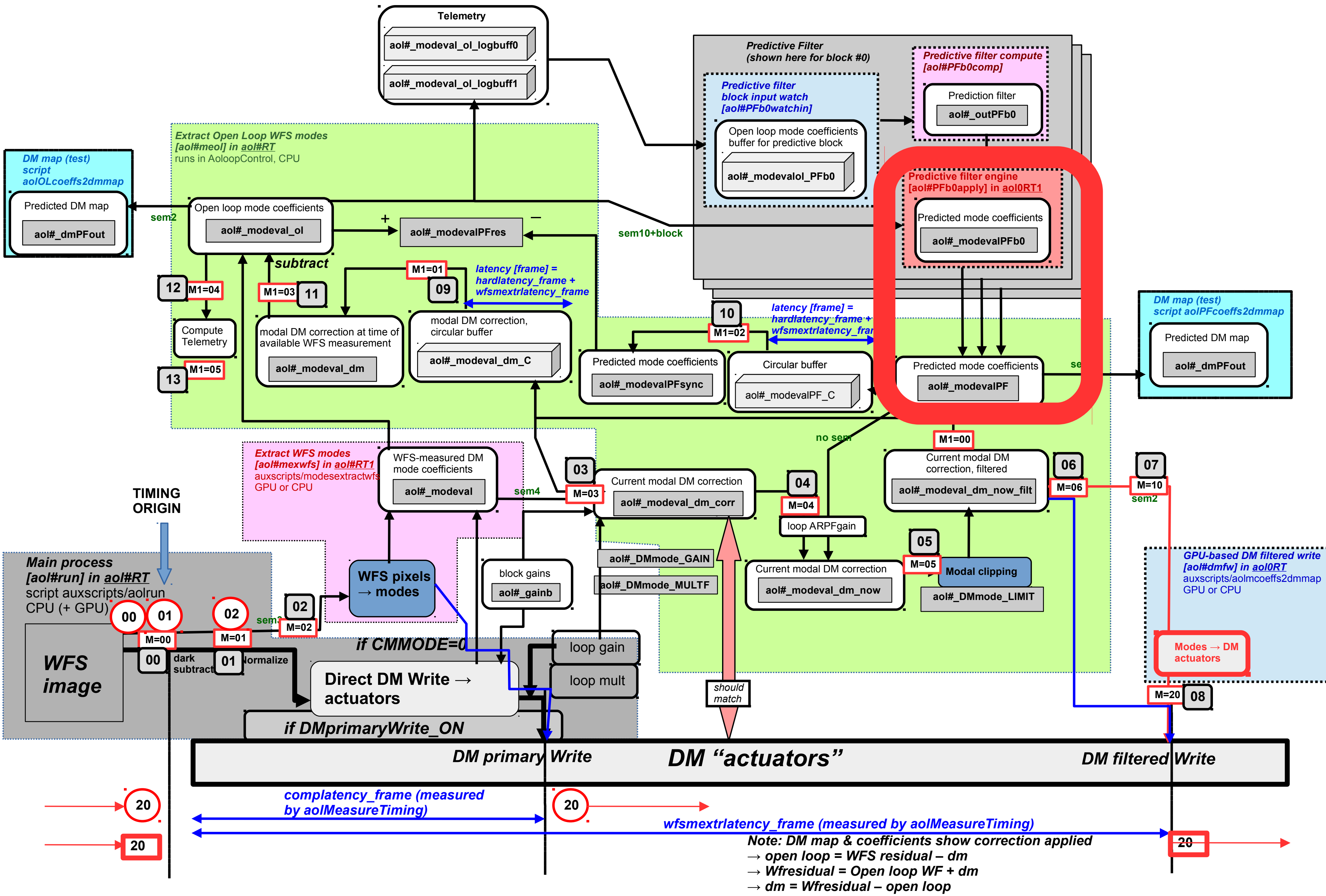
Write modal telemetry buffers



Compute Predictive Filter (soft real-time)

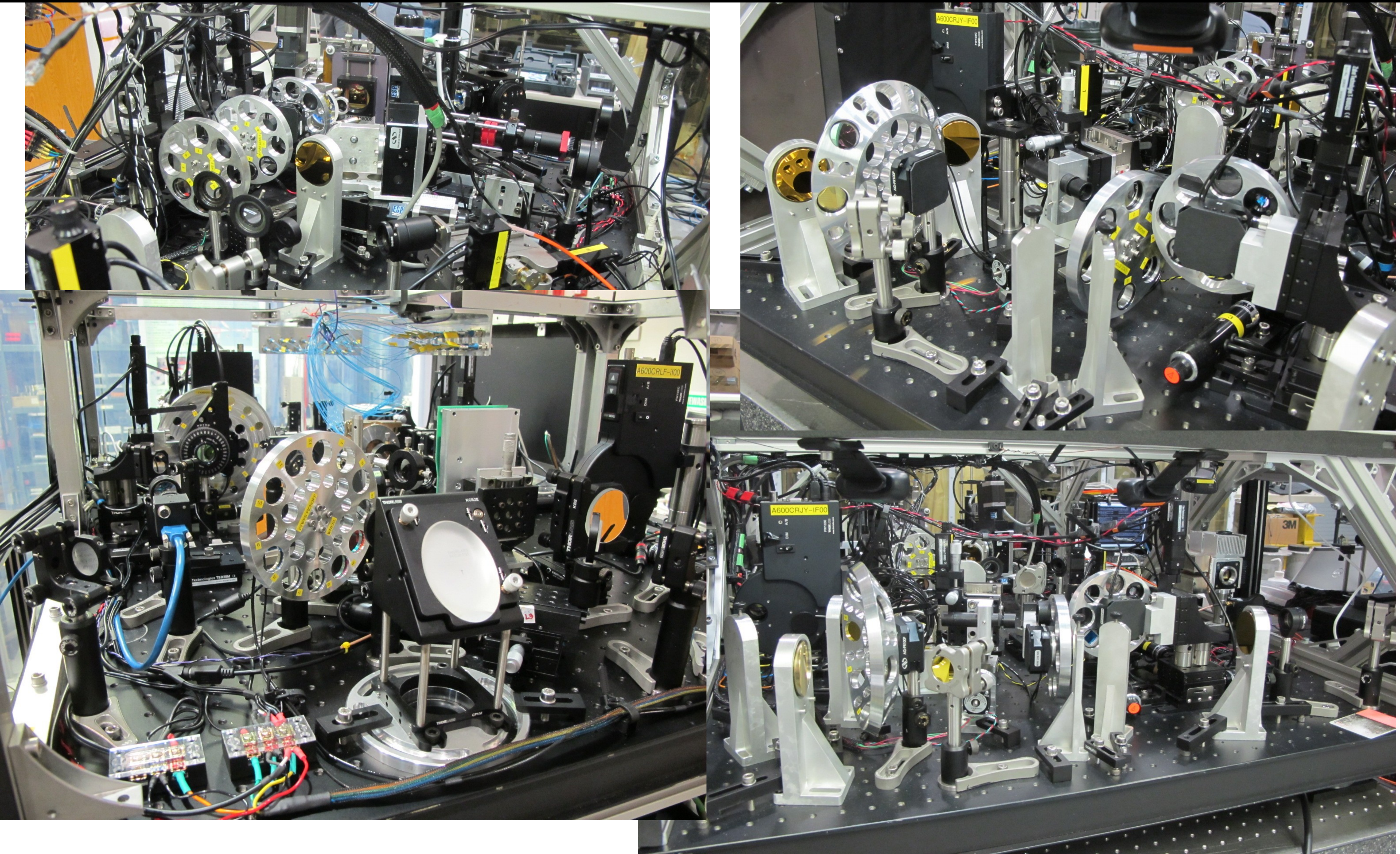


Apply Predictive Filter

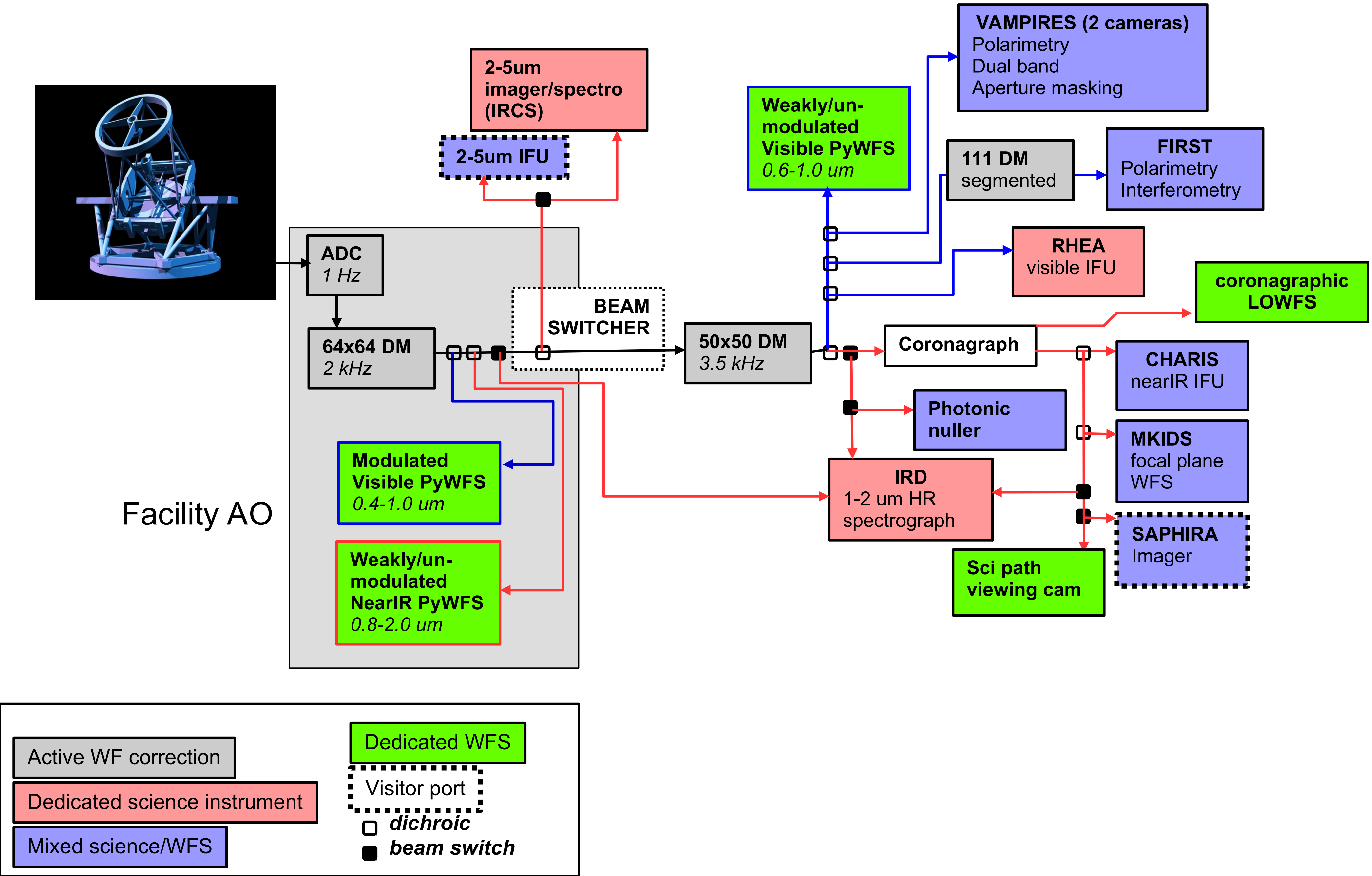


Linking loops / handling multiple WFSs and DMs

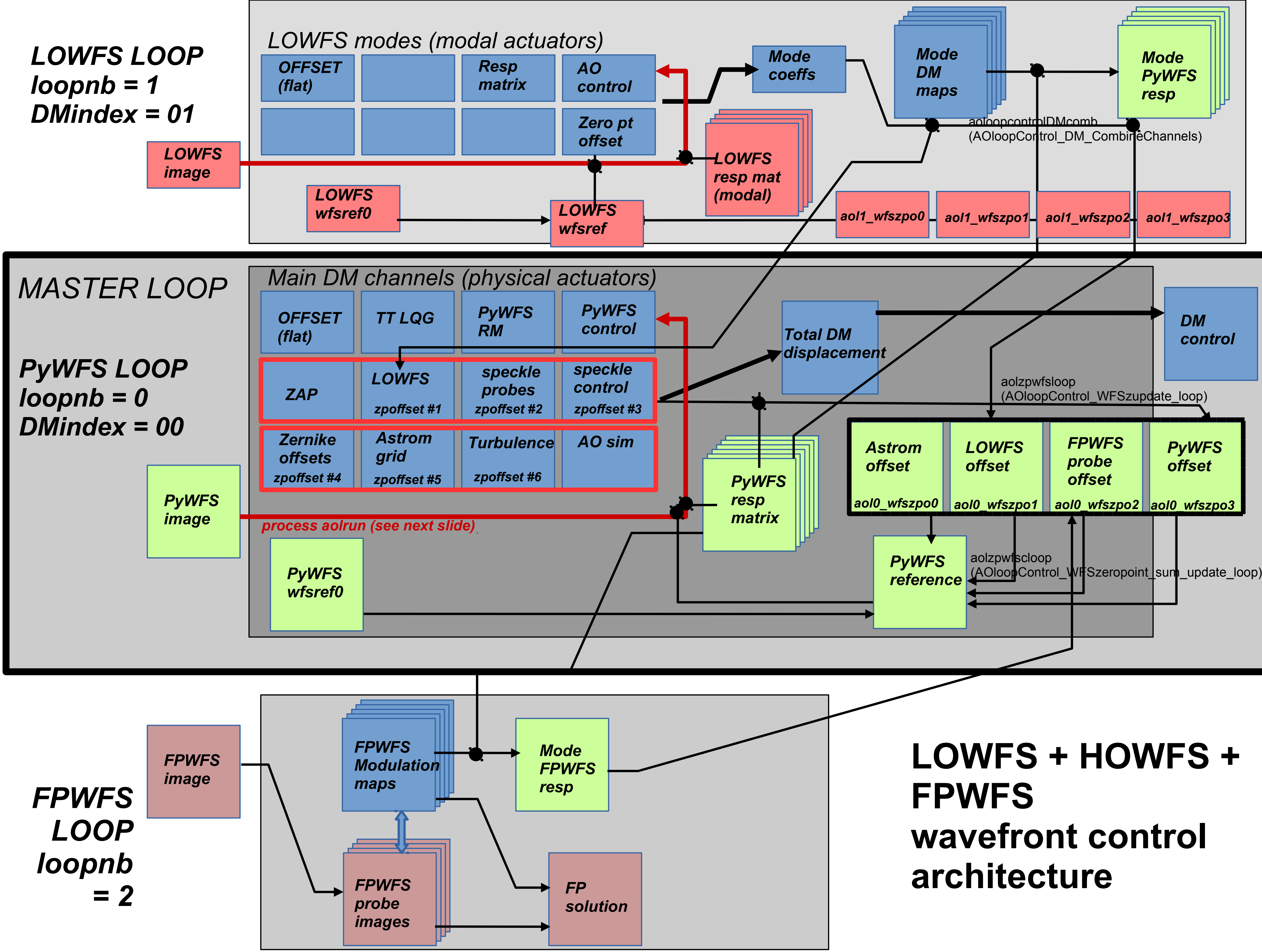
Subaru Coronagraphic Extreme Adaptive Optics



SCExAO Light path

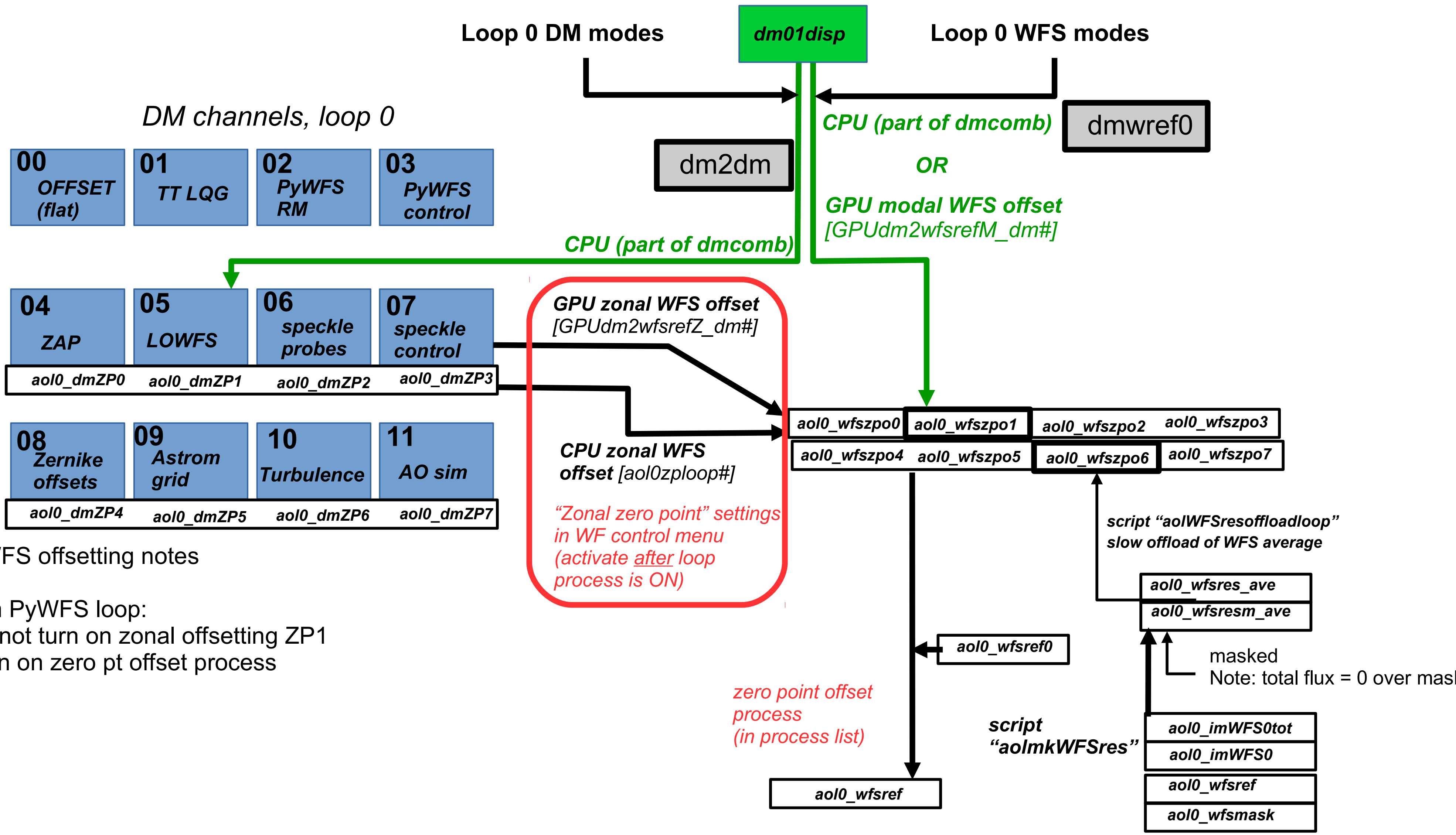


LOWFS + HOWFS + FPWFS wavefront control architecture



Linking multiple control loops (zero point offsetting)

A control loop can offset the convergence point of another loop @> kHz (GPU or CPU)
Example: speckle control, LOWFS need to offset pyramid control loop
THIS IS DONE TRANSPARENTLY FOR USER → <u>don't pay attention to the diagram below !</u>



LOWFS offsetting notes

From PyWFS loop:
- Do not turn on zonal offsetting ZP1
- Turn on zero pt offset process

Timing is everything

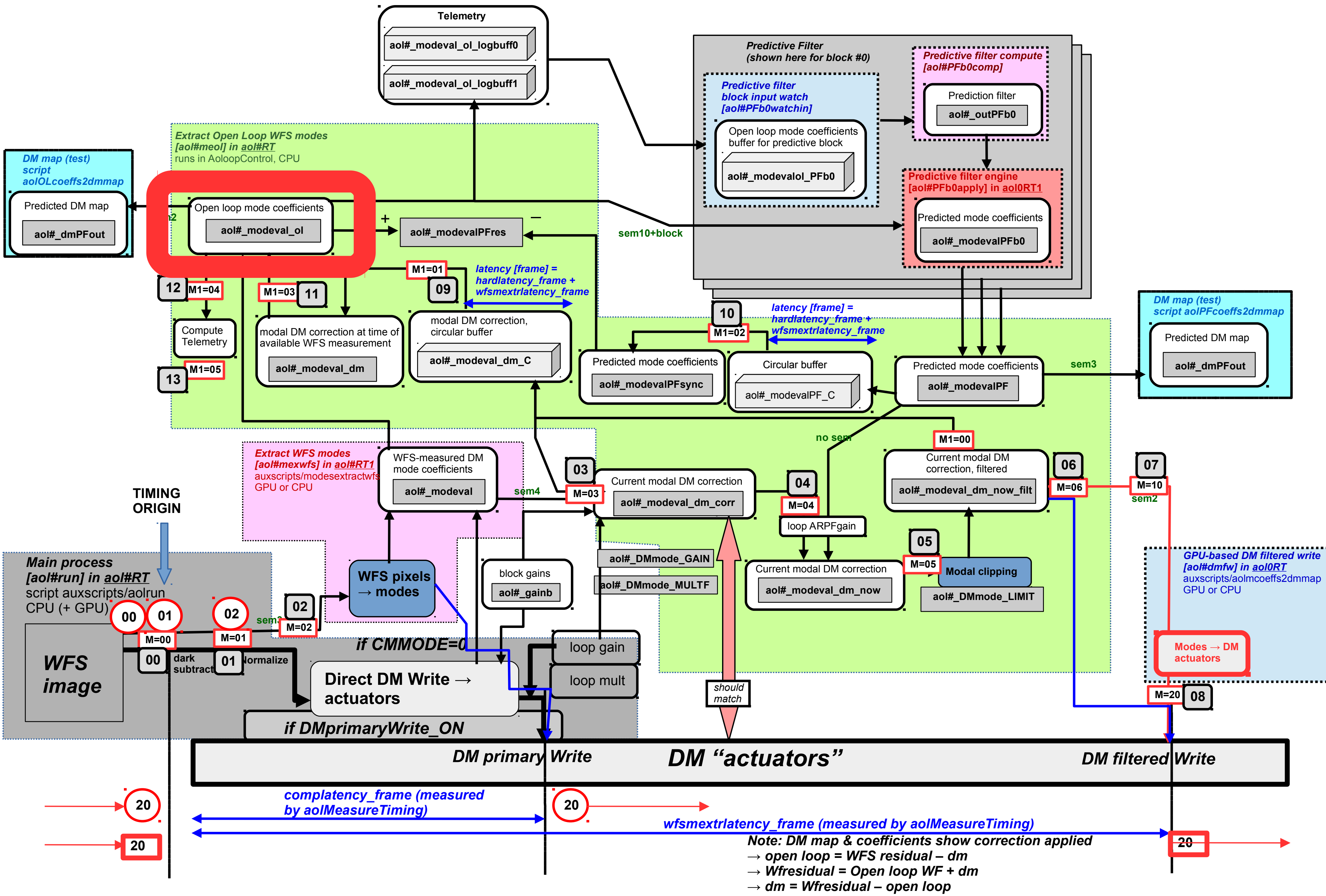
Good timing **knowledge and stability** is essential for:

→ Pseudo-open loop reconstruction

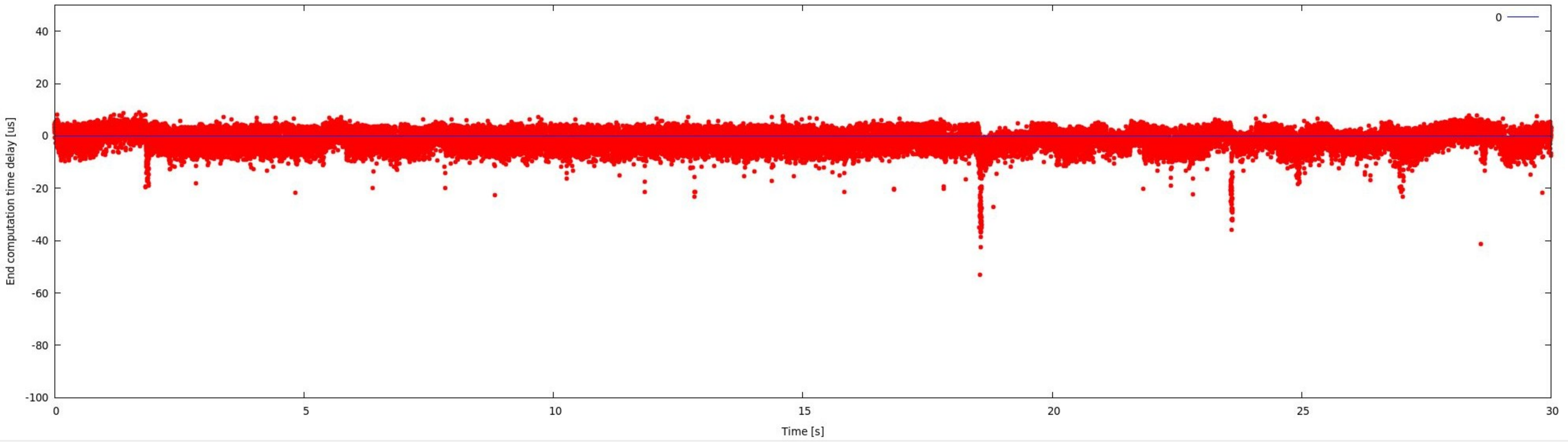
→ Fast response matrix acquisiton

→ Predictive control

End of real-time computation processes



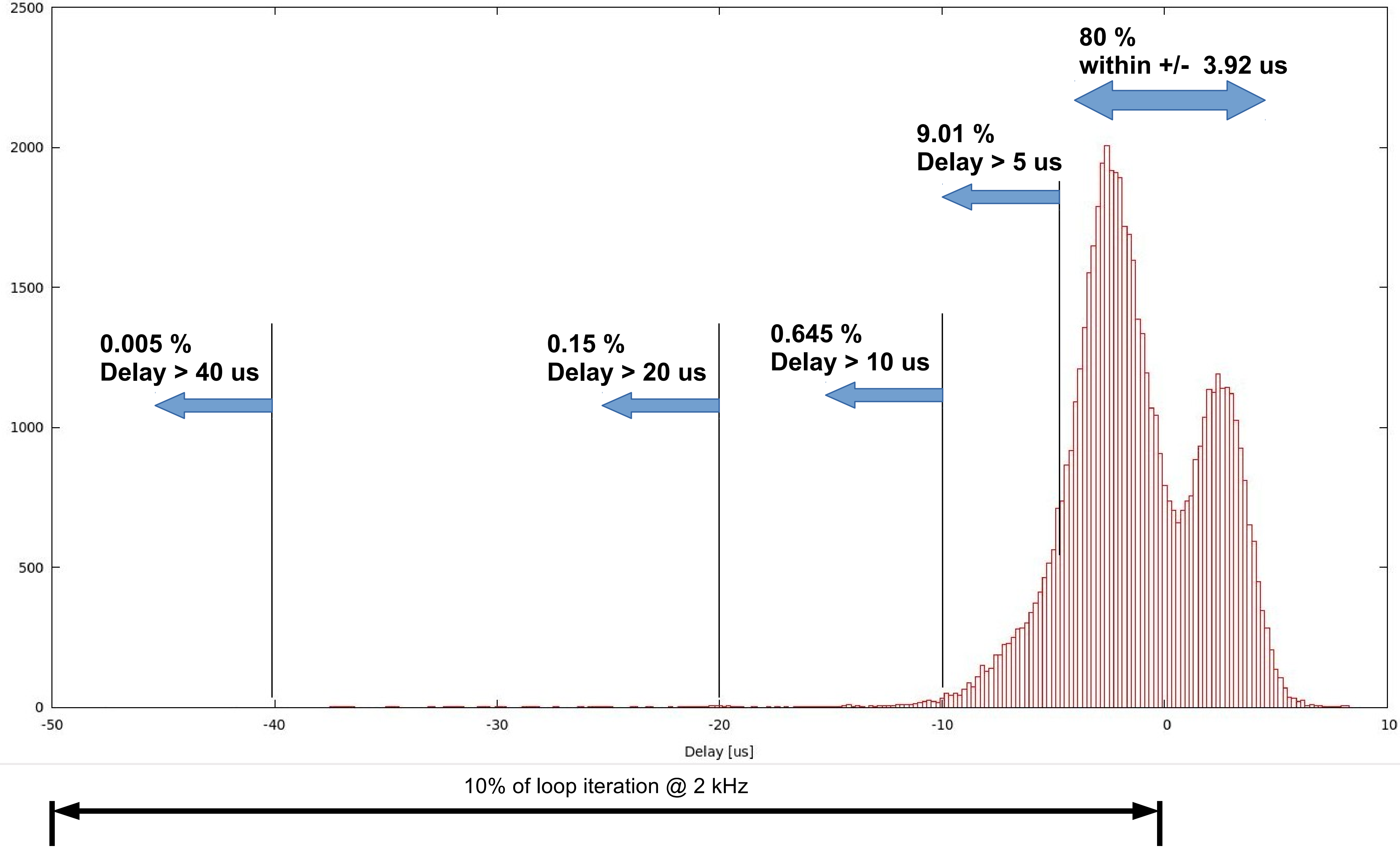
End-to-end Timing Jitter
RMS < 5 us, max delay ~50us



End-to-end timing jitter measured by monitoring completion time of last real-time stream: modal pseudo-open loop coefficients.

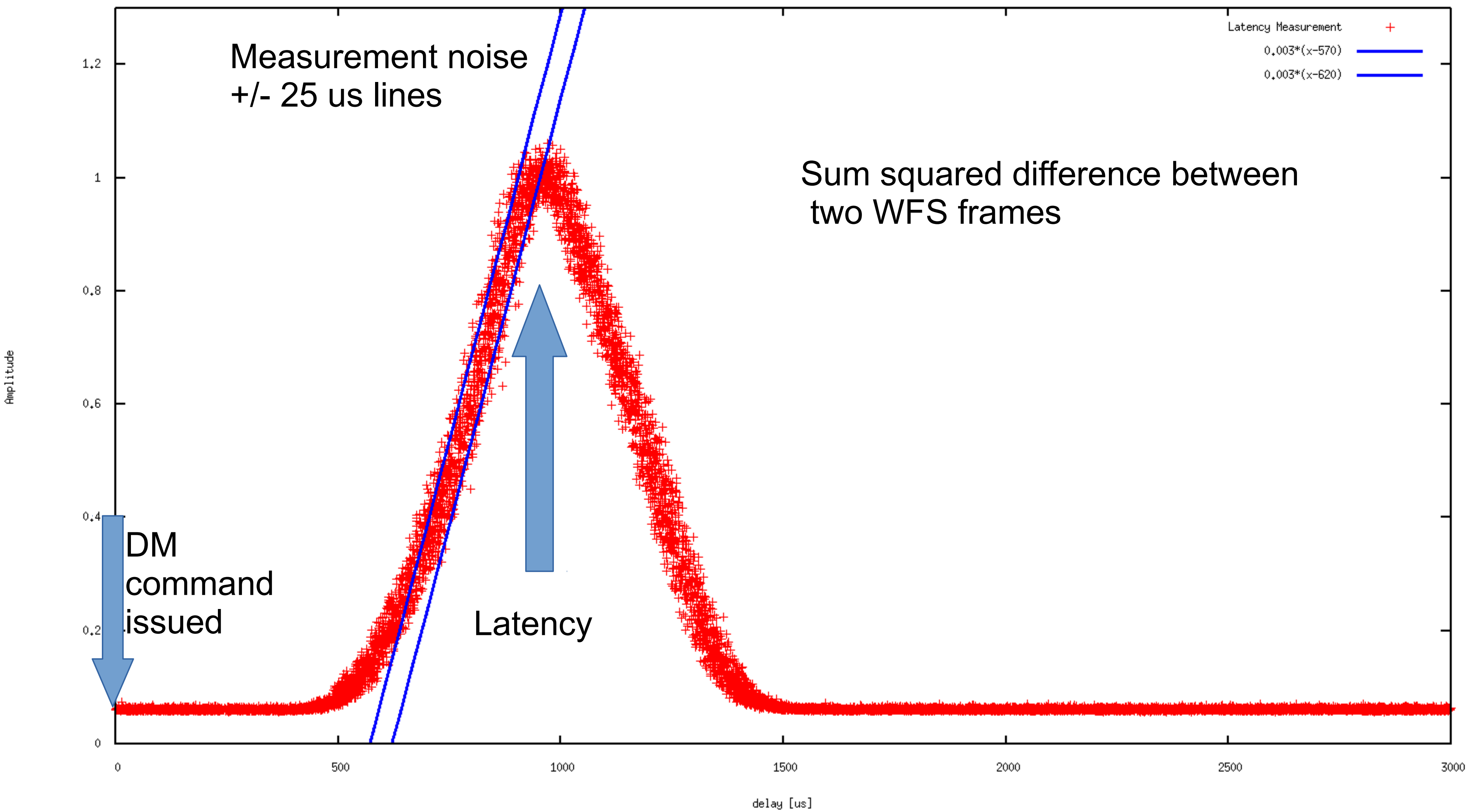
Jitter includes following components:
- Hardware synchronization (PyWFS tip-tilt mirror)
- Camera readout
- Data transfer over TCP link
- All real-time computations, CPU and GPU
- Time measurement errors

End-to-end Timing Jitter Histogram, measured @ 2kHz



Hardware Latency measured on SCExAO

Time between DM command issued and corresponding WFS signal observed
(Camera readout + TCP transfer + processing + DM electronics)



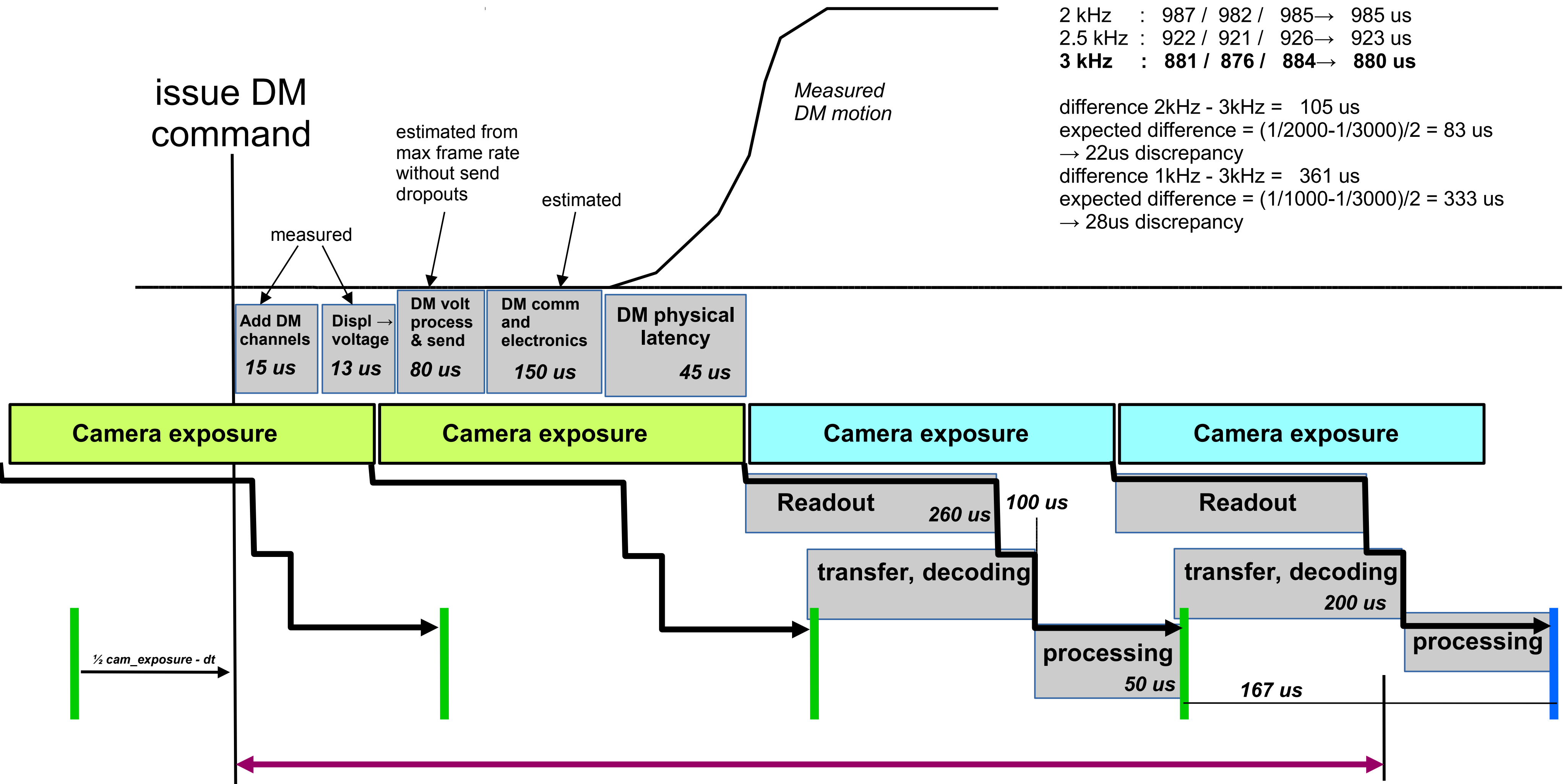
Hardware Latency

Definition:
*Time offset between **DM command issued**, and **mid-point between 2 consecutive WFS frames with largest difference***

SCExAO measured hardware latencies:

1 kHz : 1253 / 1260/ 1269 → 1261 us
1.5 kHz : 1083 / 1065/ 1081 → 1076 us
2 kHz : 987 / 982 / 985→ 985 us
2.5 kHz : 922 / 921 / 926→ 923 us
3 kHz : 881 / 876 / 884→ 880 us

difference 2kHz - 3kHz = 105 us
expected difference = (1/2000-1/3000)/2 = 83 us
→ 22us discrepancy
difference 1kHz - 3kHz = 361 us
expected difference = (1/1000-1/3000)/2 = 333 us
→ 28us discrepancy

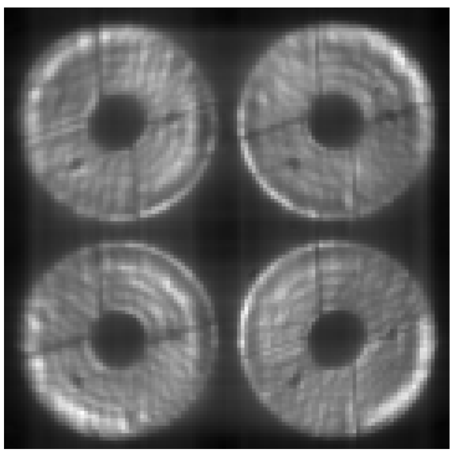


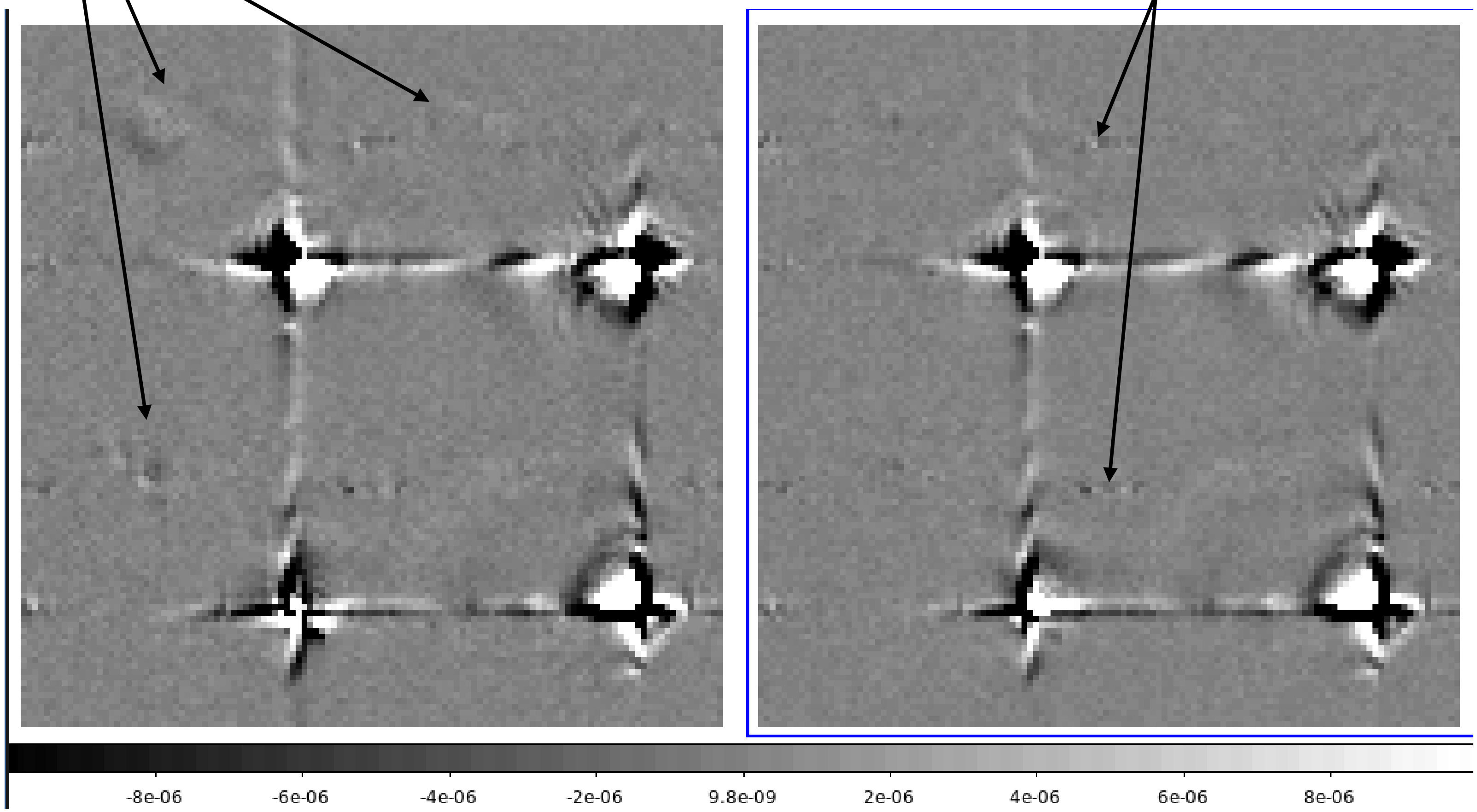
HardwareLatency = DM soft + DM elec + DM phys + CAM readout/transfer + CAM processing + ½ exposure time
HardwareLatency = N x cam_exposure + dt

Fast RM acquisition (4000 Hadamard pokes in 2s @ 2 kHz) + Removing temporal DM response from response matrix by using two poke sequences

Temporal bleeding from previous poke pattern (should be removed from RM)

Camera readout RF coupling between pixels
~1% electronic ghosts at 2kHz frame rate
Needs to be kept in RM



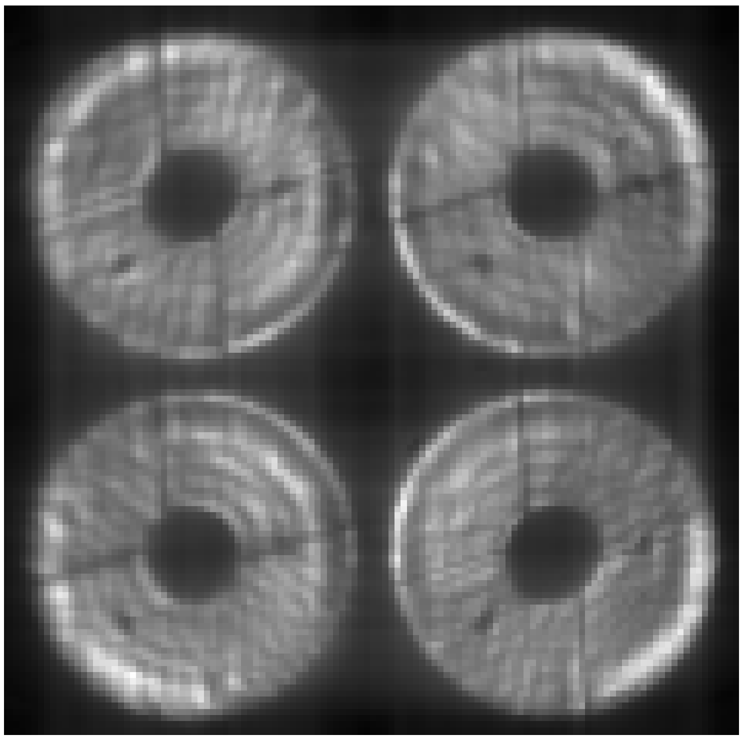


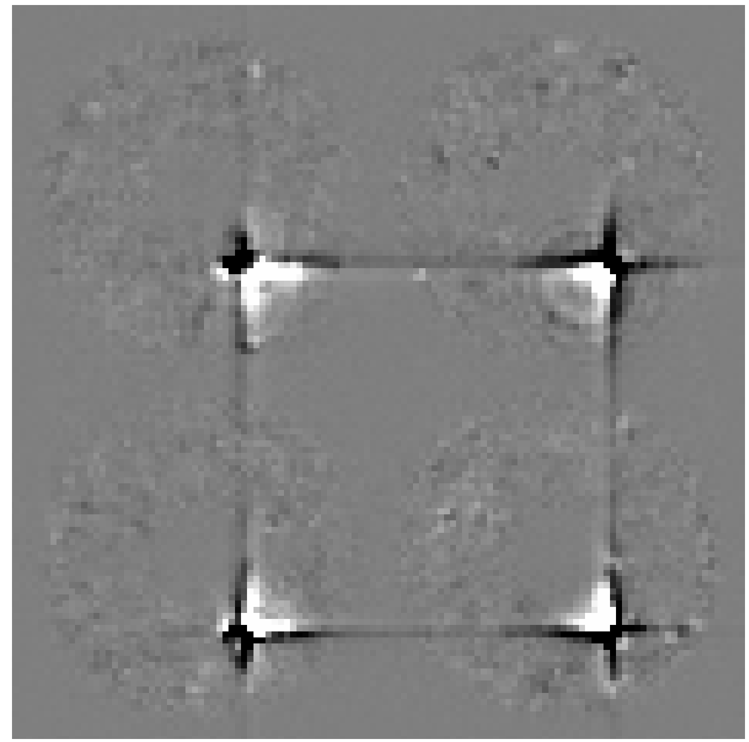
RM assembled from single poke sequence:
+- +- +- +-

RM assembled from average of two poke sequences:
+- +- +- +-
+- -+ +- -+

RMs reconstructed from Hadamard pokes, 2kHz modulation (DM moves during EMCCD frame transfer)

Multi-channel DM virtualization & timing knowledge/stability → on-sky response matrix acquision, while ExAO loop running





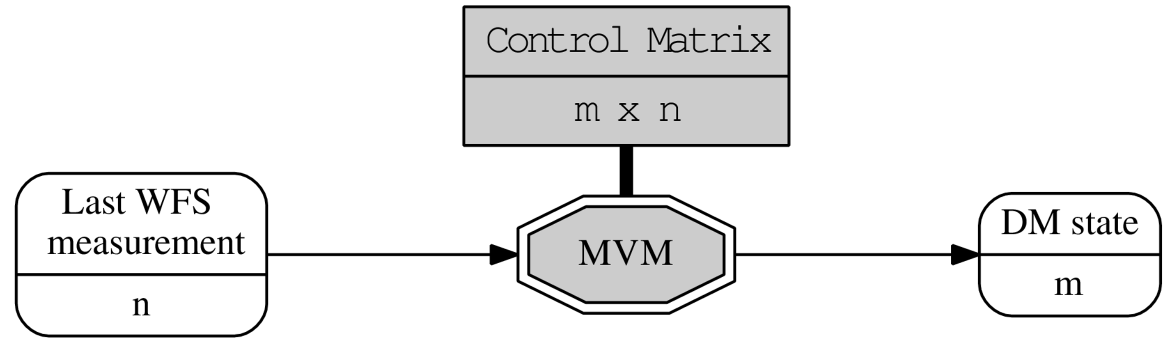
Left: WFS reference
Right: Response to single actuator poke (one of 2000)

RM measurement @ 2kHz takes 4000 pokes = 2 sec
Multiple RMs averaged to increase SNR

Self-learning AO control

Conventional AO:

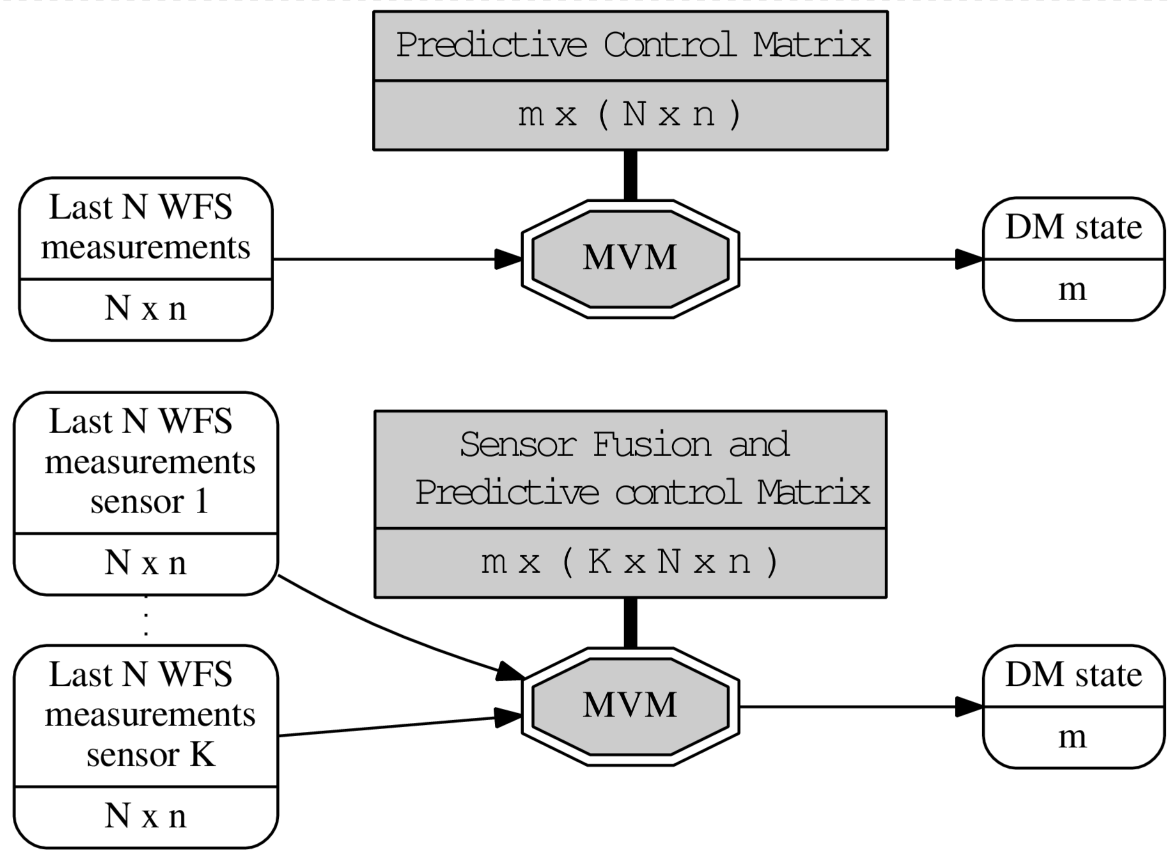
Resp Matrix is **measured**
CM computed as pseudo-inverse of RM



Self-learning AO control:

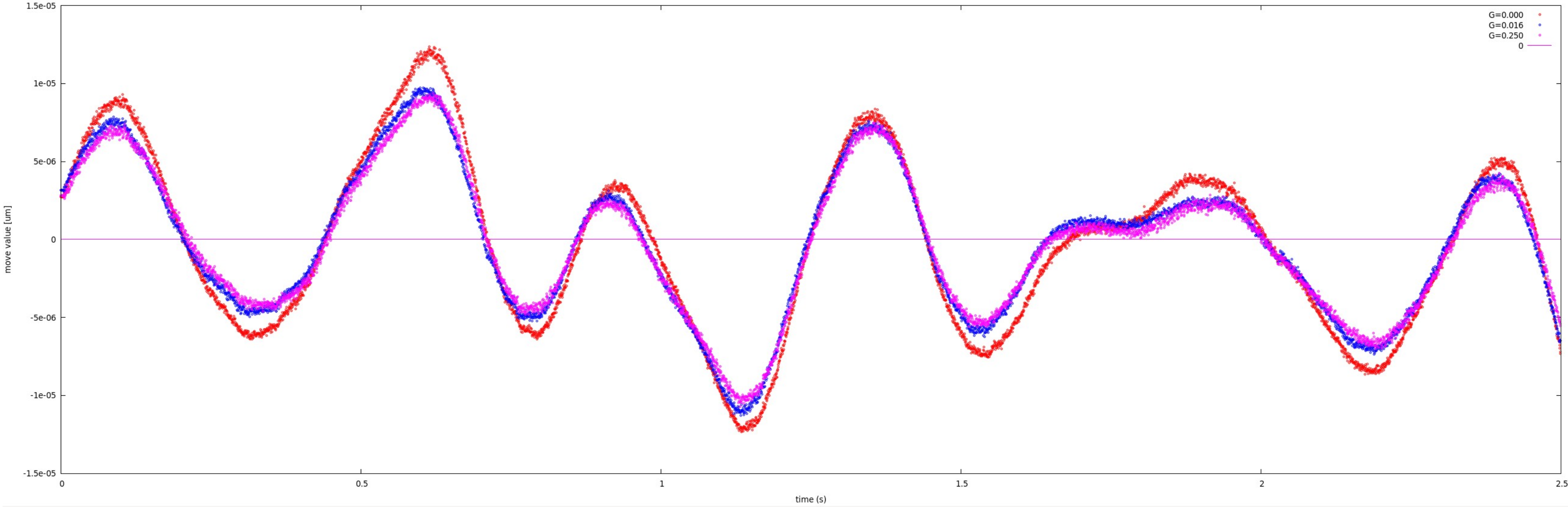
Optimally use recent (predictive control) and auxiliary (sensor fusion) measurements→ control matrix is very big, and usually impossible to measure

CM is **derived** from WFS(s) telemetry using machine learning approaches



Open loop reconstruction
Comparison between gain values

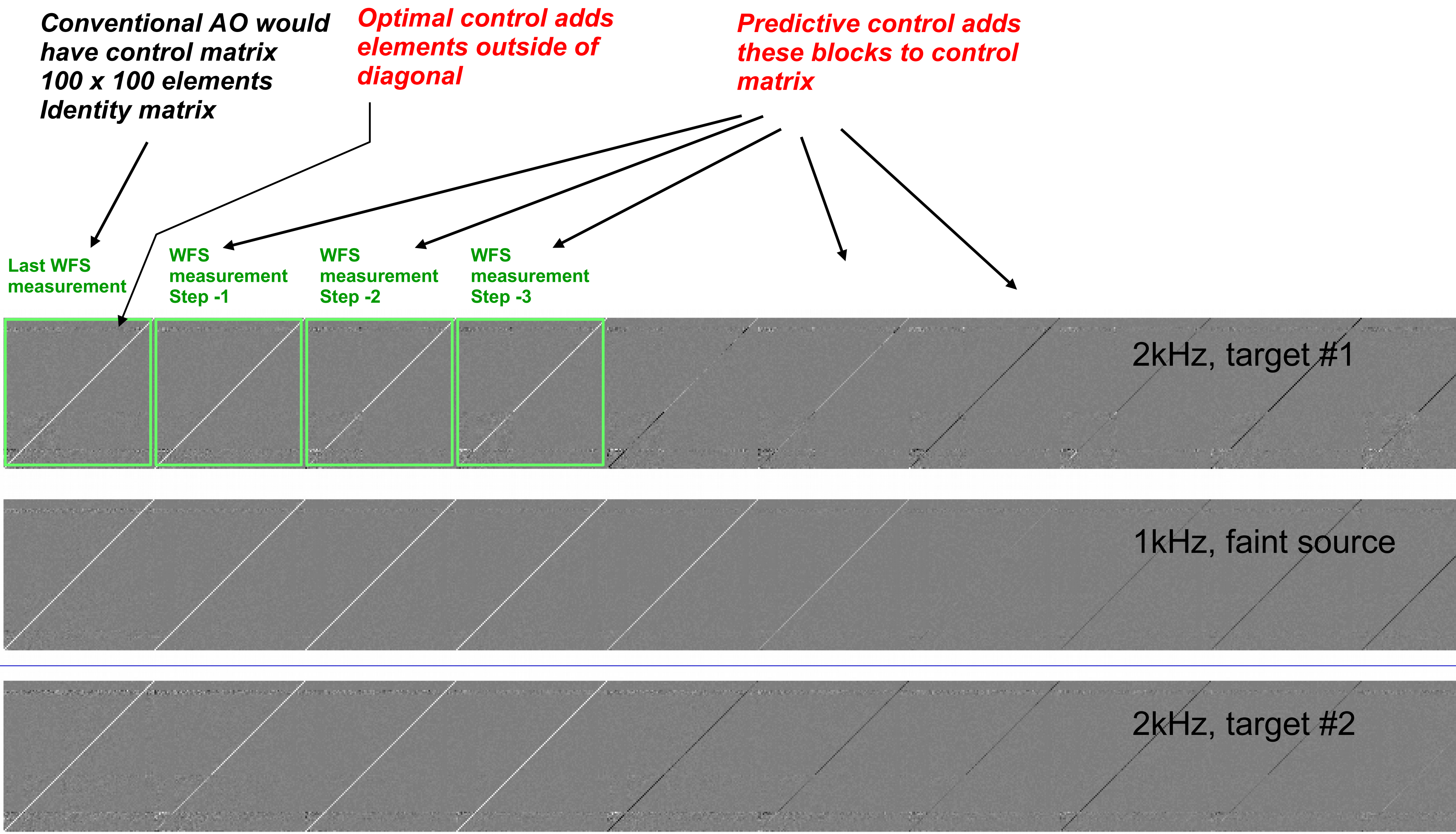
G=0.000 → over-estimates OL values
All G>0.0 reconstructions match at %-level



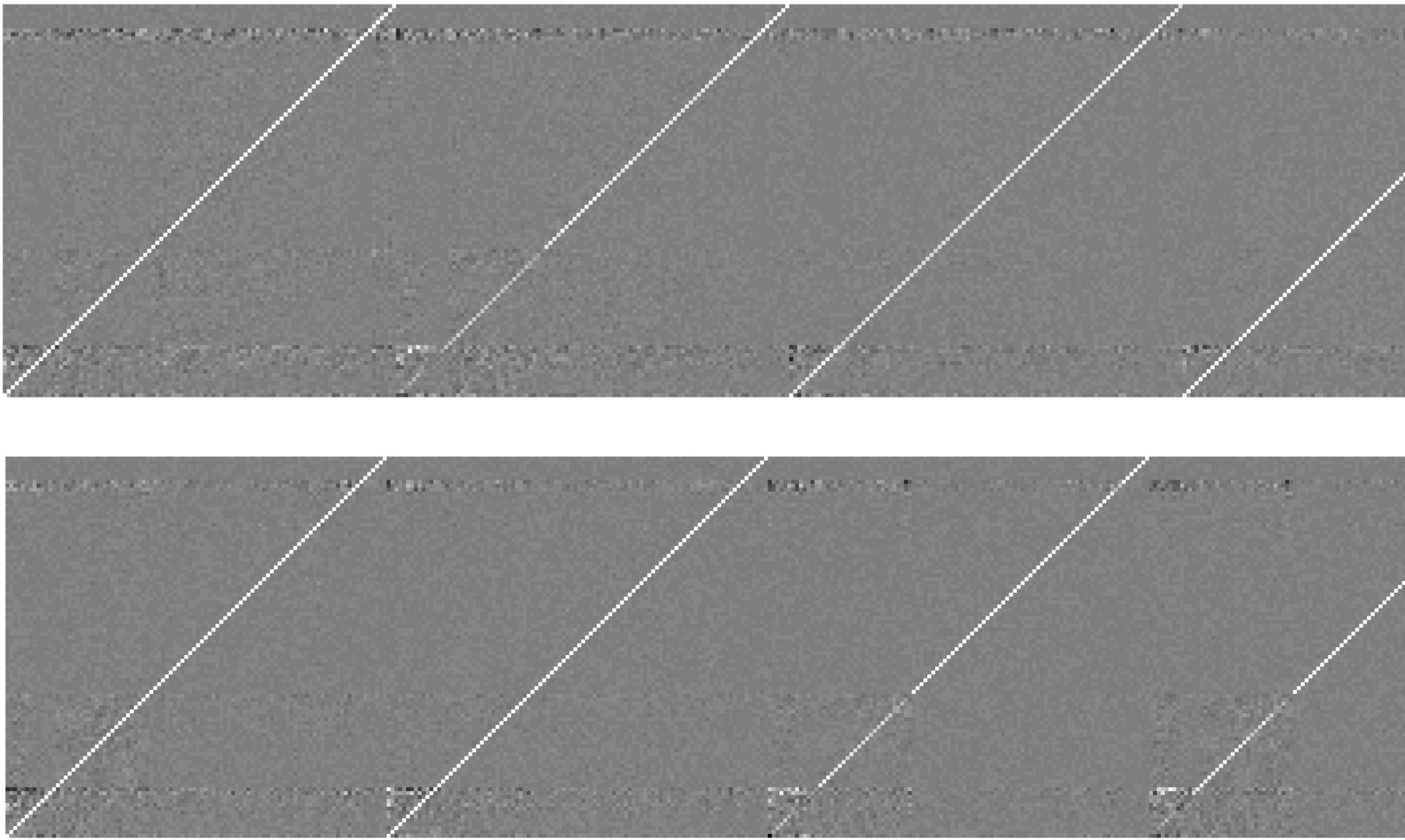
G=0.000 test relies entirely on WF residuals for OL estimation
G>0.000 tests rely mostly on DM values for OL estimation

Test shown here uses full speed RM acquisition which underestimates RM by ~15% due to DM time-of-motion → reconstructed WFs from WFS are over-estimated by ~15%

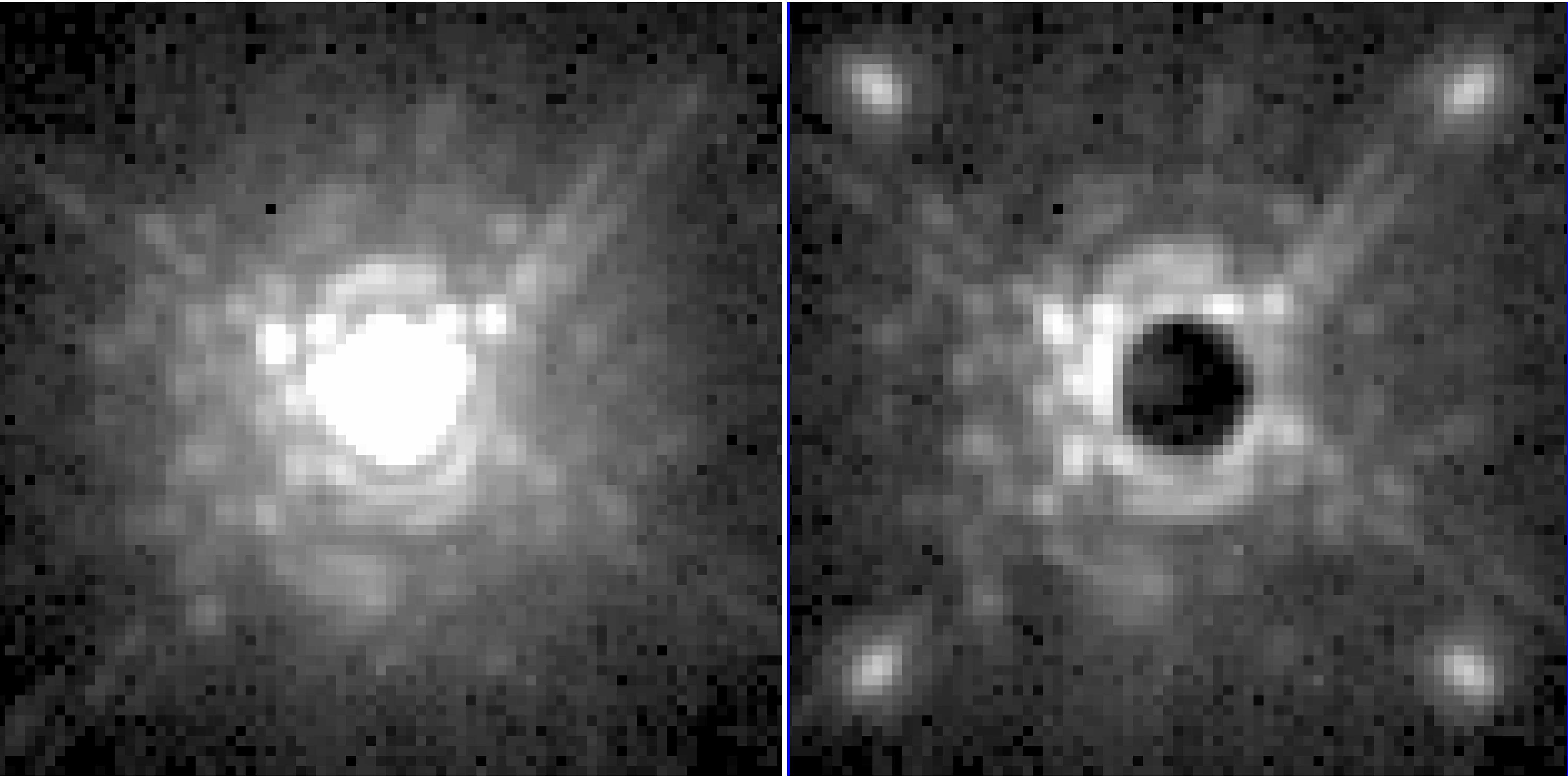
On-sky predictive control matrix (modal representation, 100 modes shown)



Prediction control matrix



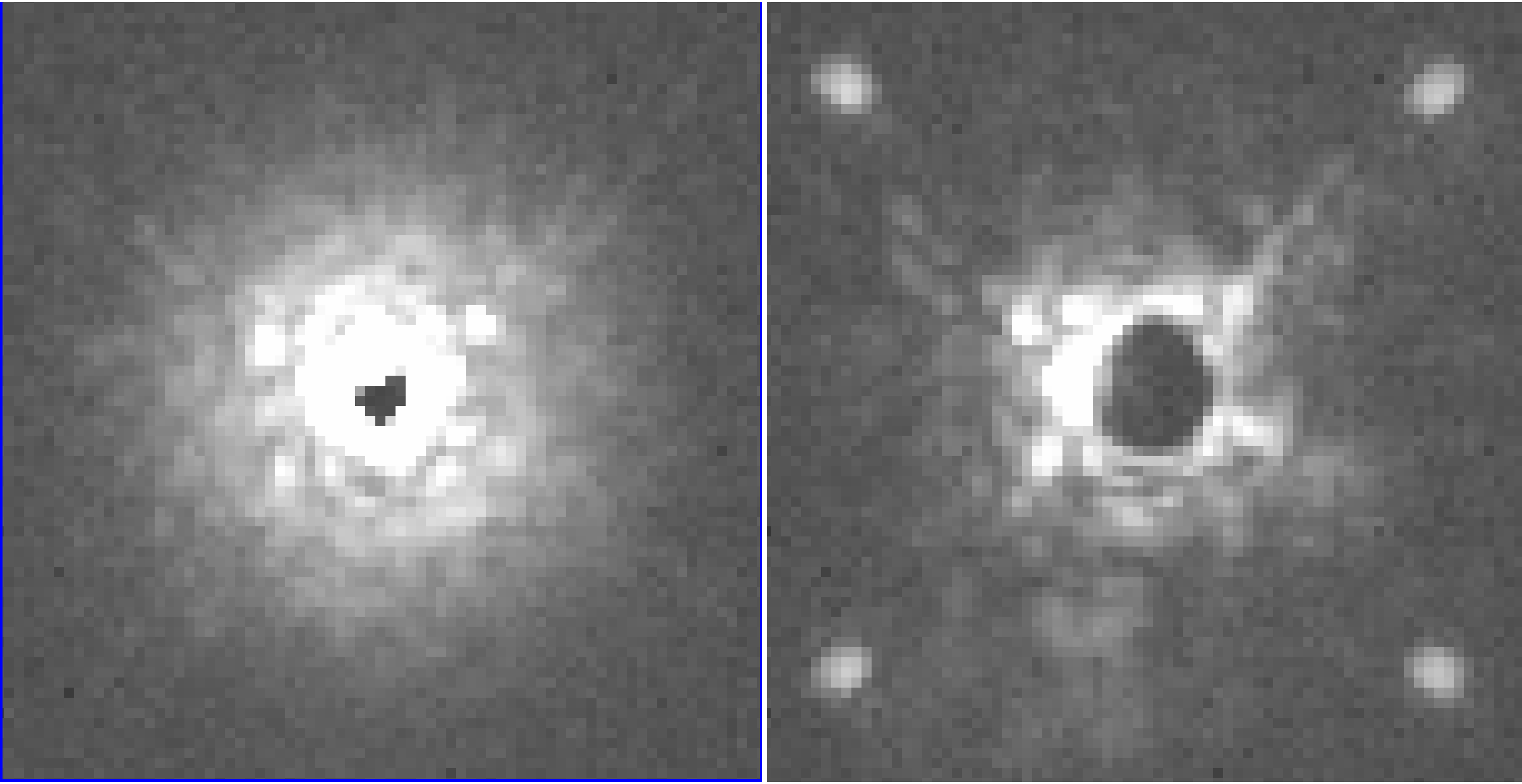
On-sky results (2 kHz, 50 sec update)



OFF (integrator, gain=0.2) ***ON***

Average of 54 consecutives 0.5s images (26 sec exposure), 3 mn apart
Same star, same exposure time, same intensity scale

Standard deviation improved by 2.5x

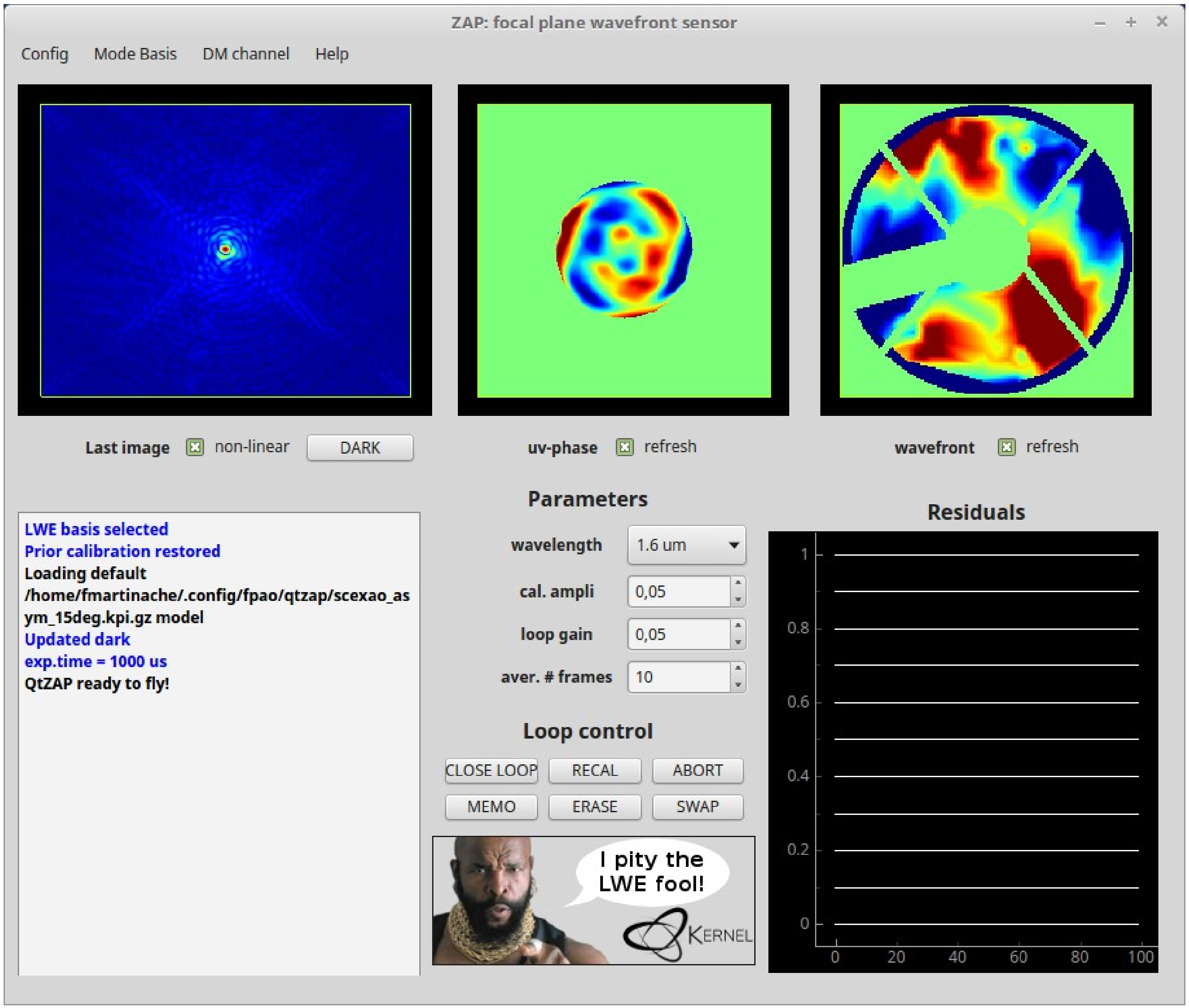


OFF (integrator, gain=0.2) ***ON***

Standard deviation of 54 consecutives 0.5s images (26 sec exposure), 3 mn apart
Same star, same exposure time, same intensity scale

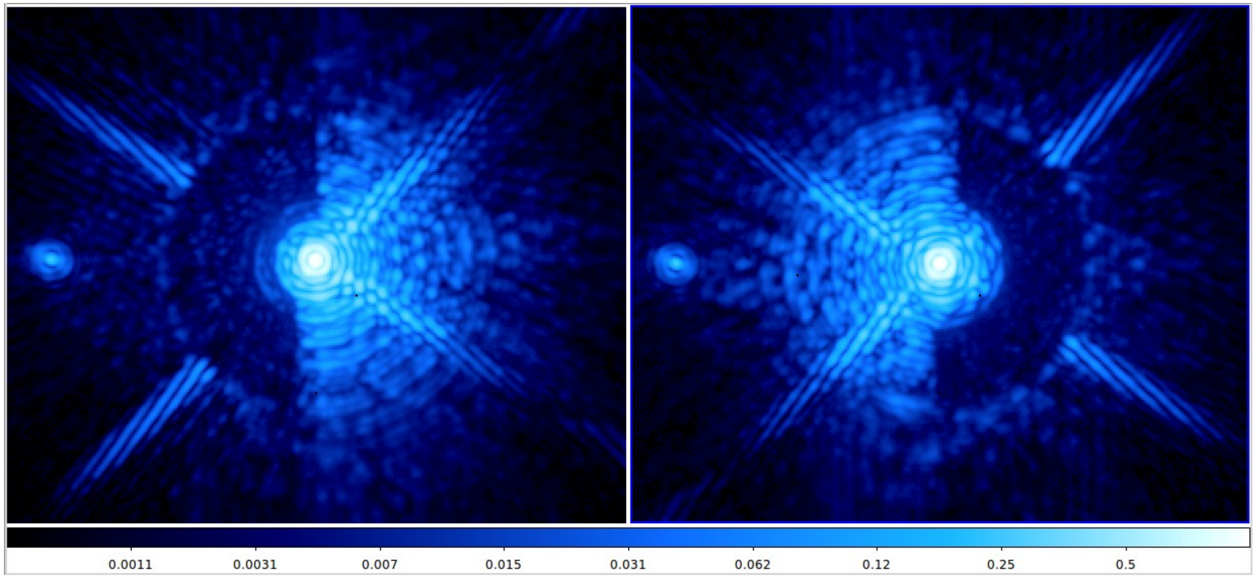
Focal Plane WFS/C

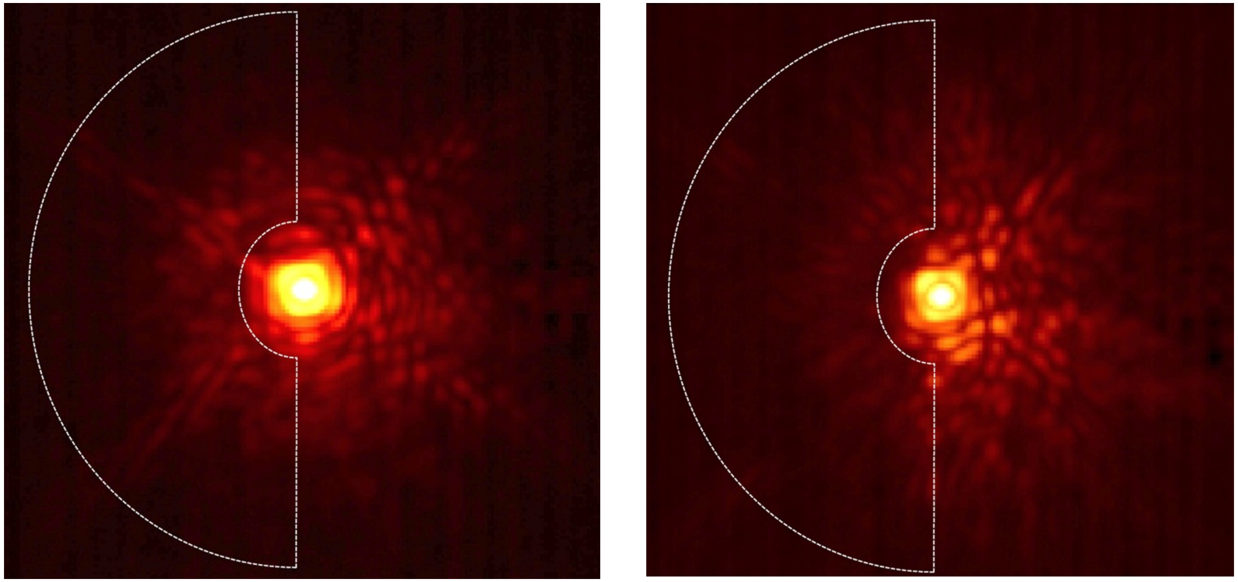
OCA/KERNEL – developed software



- Address NCPA
- Asymmetric mask (pupil)
- On-sky closed-loop control
- Focal plane based WFS Low-order (Zernike and LWE) modes.
- mode compatible with coronagraphy in development

Speckle Control





Speckle nulling, in the lab and on-sky (no XAO).

Experience limited by detector readout noise and speed.

KERNEL project: C-RED-ONE camera.

From:
- 114 e- RON
- 170 Hz frame rate

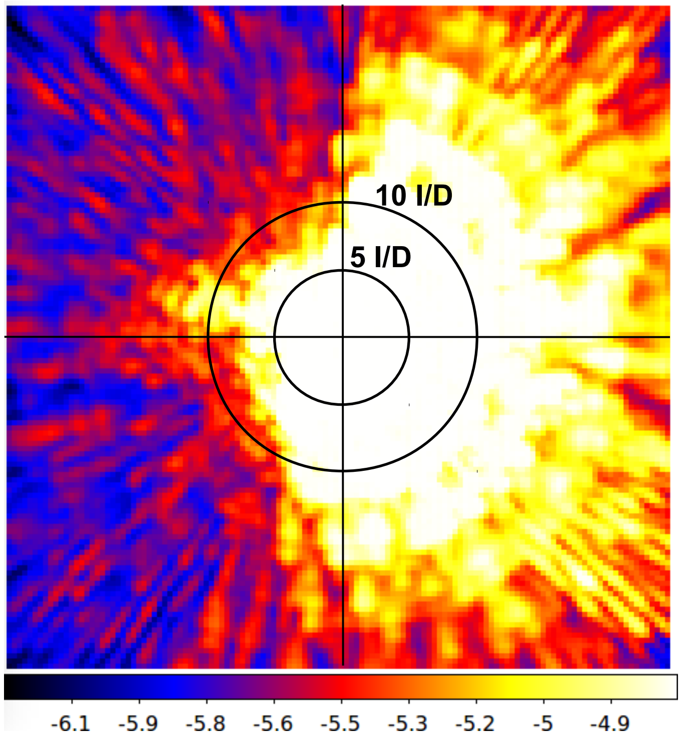
To:
- 0.8 e- RON
- 3500 Hz frame rate

Expect some updates

Observatoire de la CÔTE d'AZUR

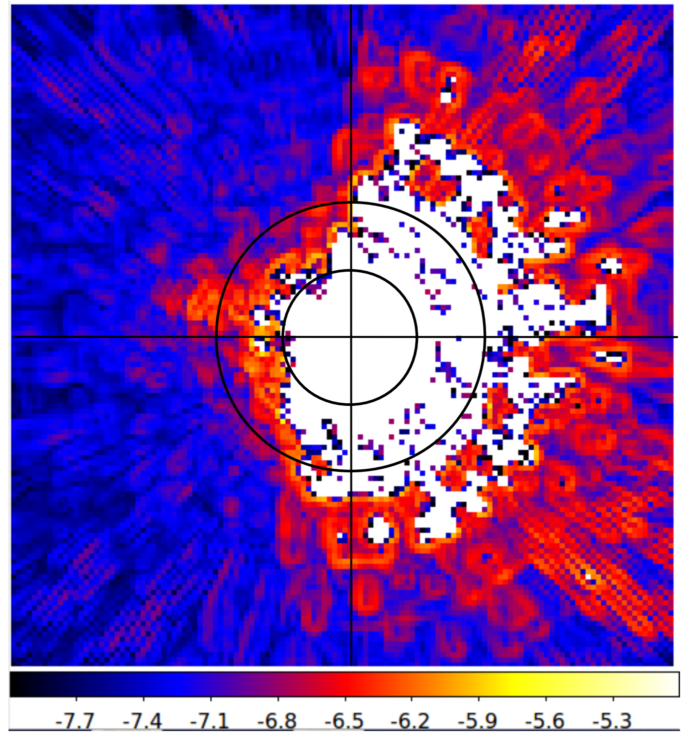
Conventional Lyot Coronagraph, Broadband light: 0.9-1.7 um (62% wide band)

Raw Contrast



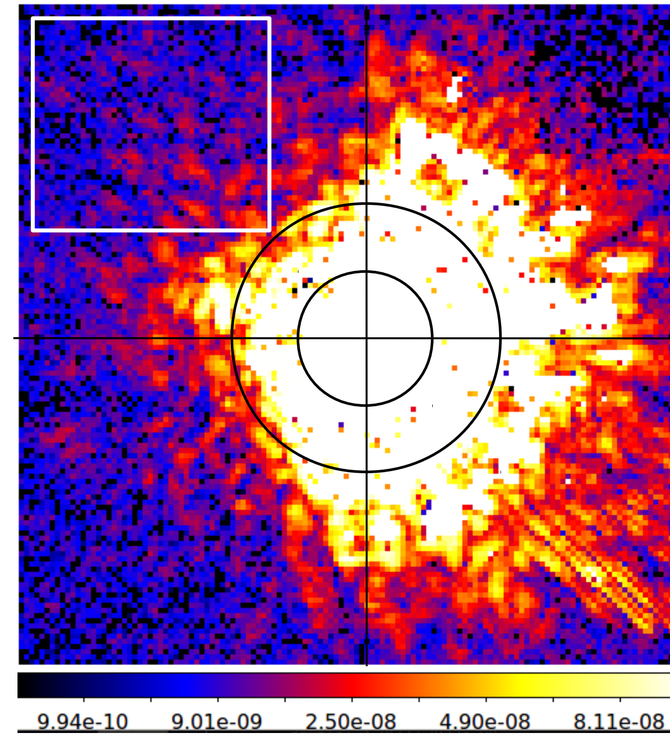
Average raw contrast [15-20 l/D]
= 2.3e-6

Open-loop contrast stability

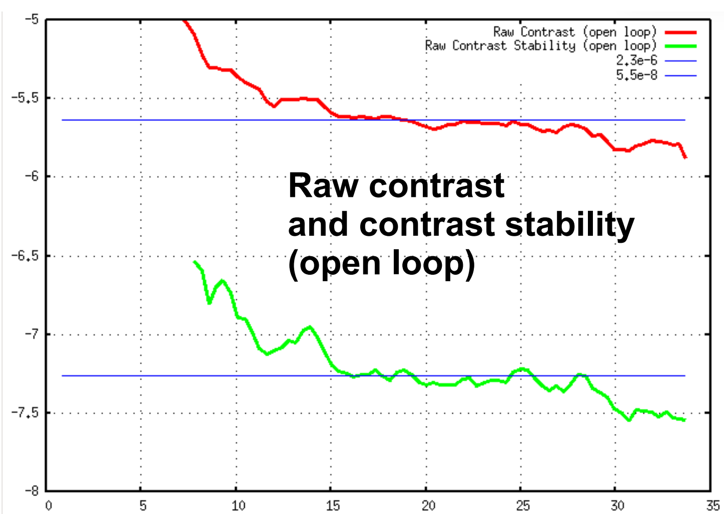


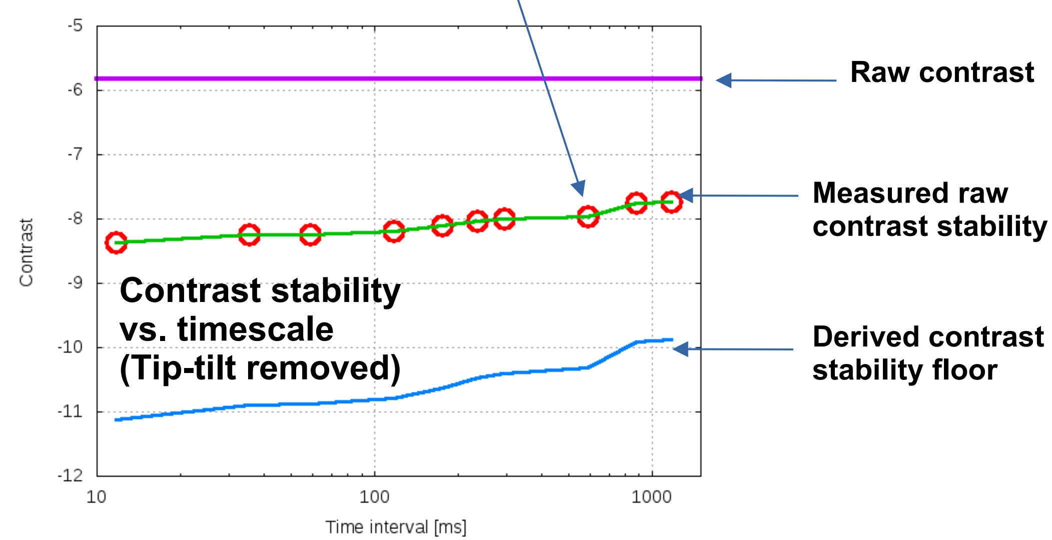
Average raw contrast stability [15-20 l/D]
= 5.5e-8

Contrast stability over 0.6 sec



Average raw contrast stability [11-34 l/D]
= 1.1e-8 (averaged value within white box)

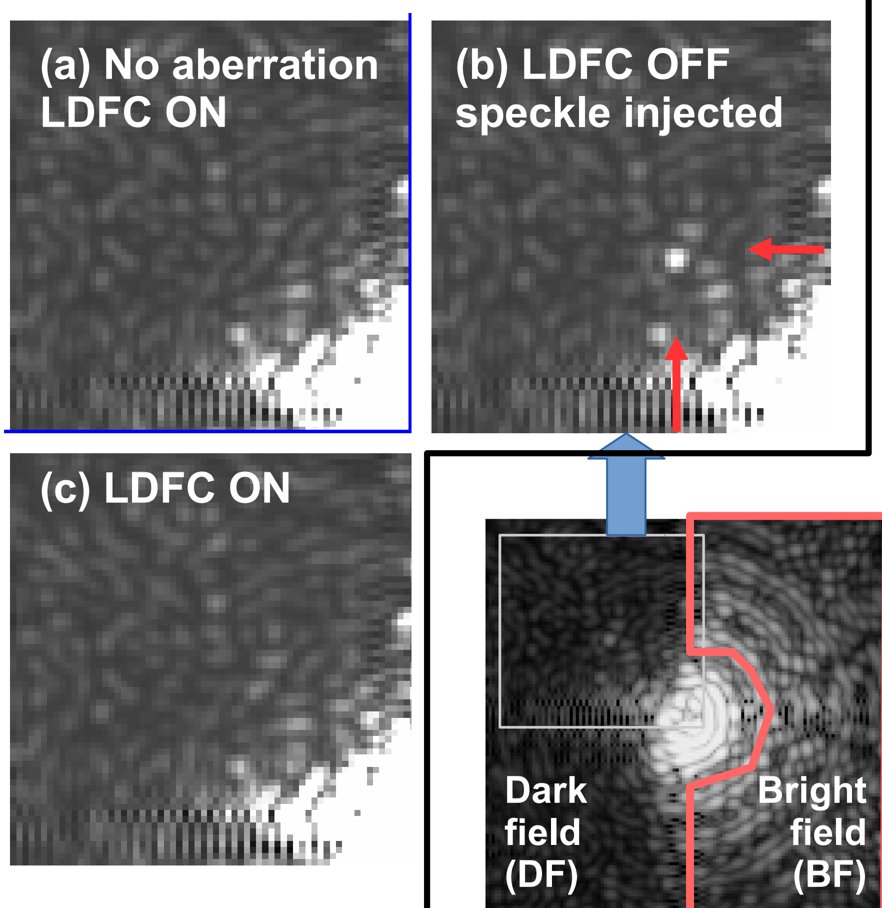




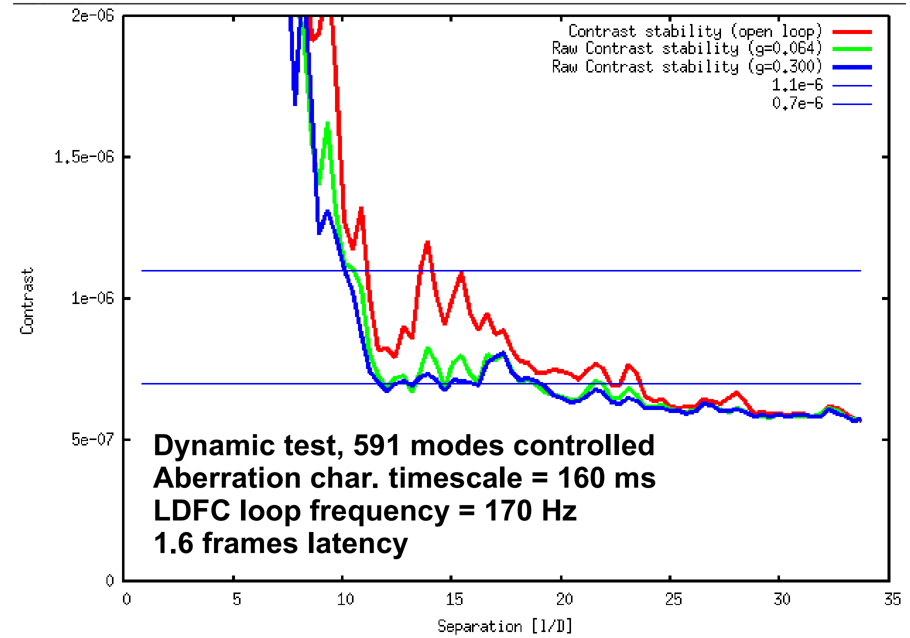
Linear Dark Field Control (internal source)

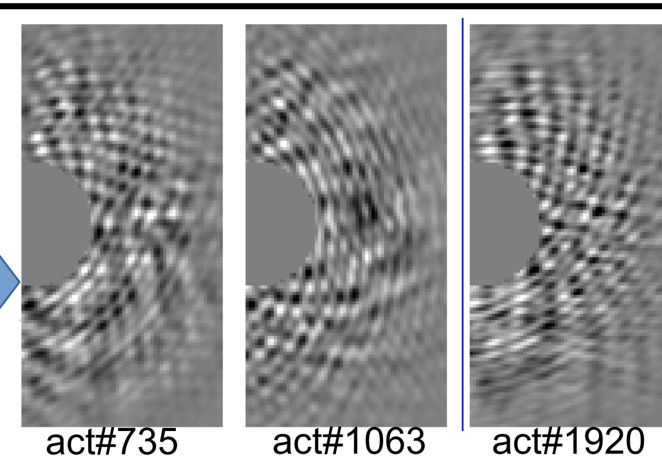
Near-IR spatial LDFC validation @ SCExAO
Frame rate = 170 Hz, Lyot coronagraph in near-IR
(1.55um, 50nm wide band)

C=1.25e-5 speckle at 13 λ/D separation



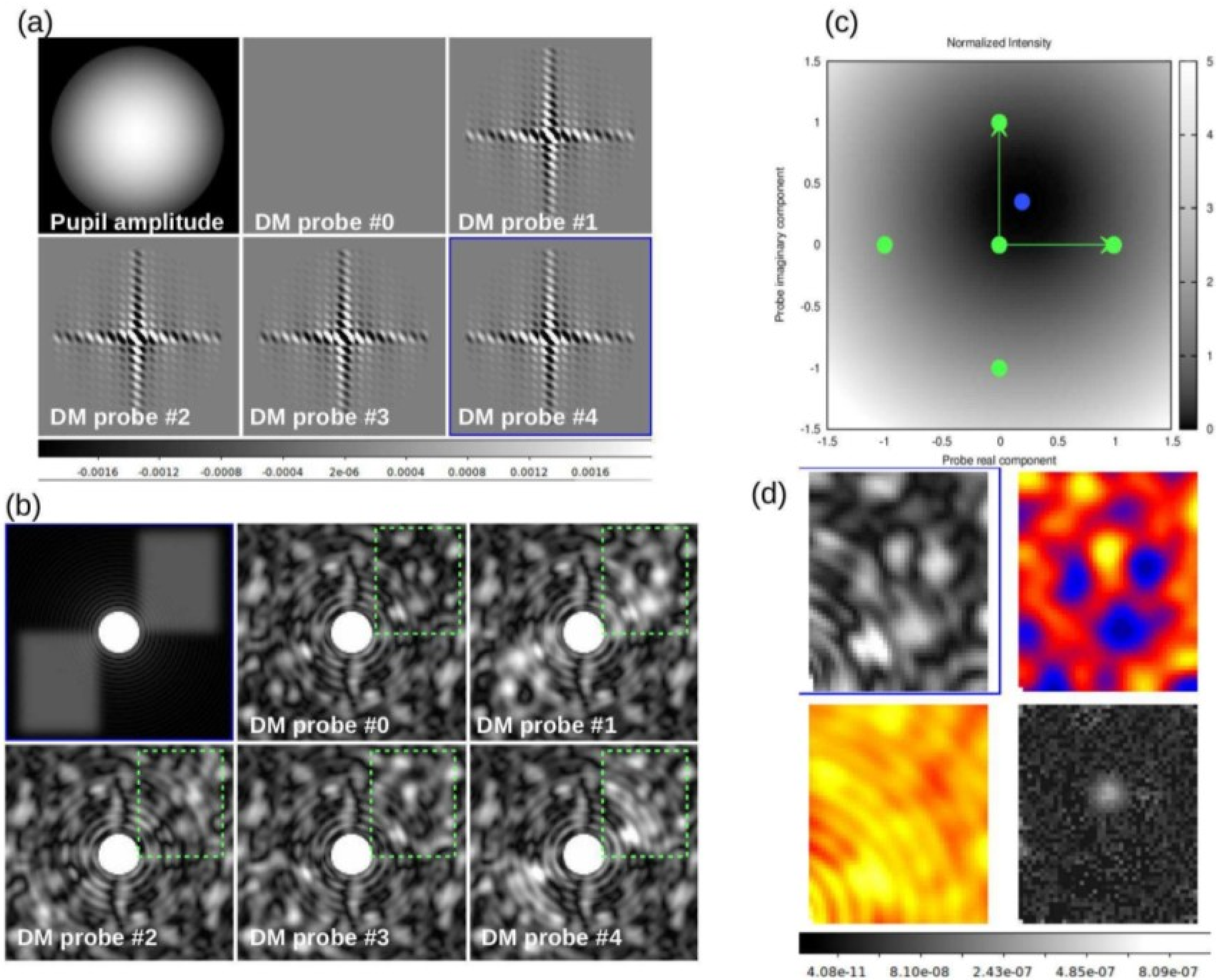
LDFC contrast stabilization





Measured LDFC BF signal response to single actuator poke

Coherent Speckle Differential Imaging



Thank you !

https://github.com/cacao-org/cacao