Jet Propulsion Laboratory
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Update for SITs on CGI processing and wavefront sensing and control baseline and plans

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Overview

CGI is still assembling an official policy on accepting algorithm contributions. We will present it at a future Stanford meeting.

For benefit of interested parties, we cover the following items today, related to planned CGI capabilities:

- **Review of CGI hardware baseline**
- **Review of CGI telemetry baseline and data rate**
- **Review of CGI high-order WFSC software baseline and schedule**
- **Path to updates of CGI behaviors**

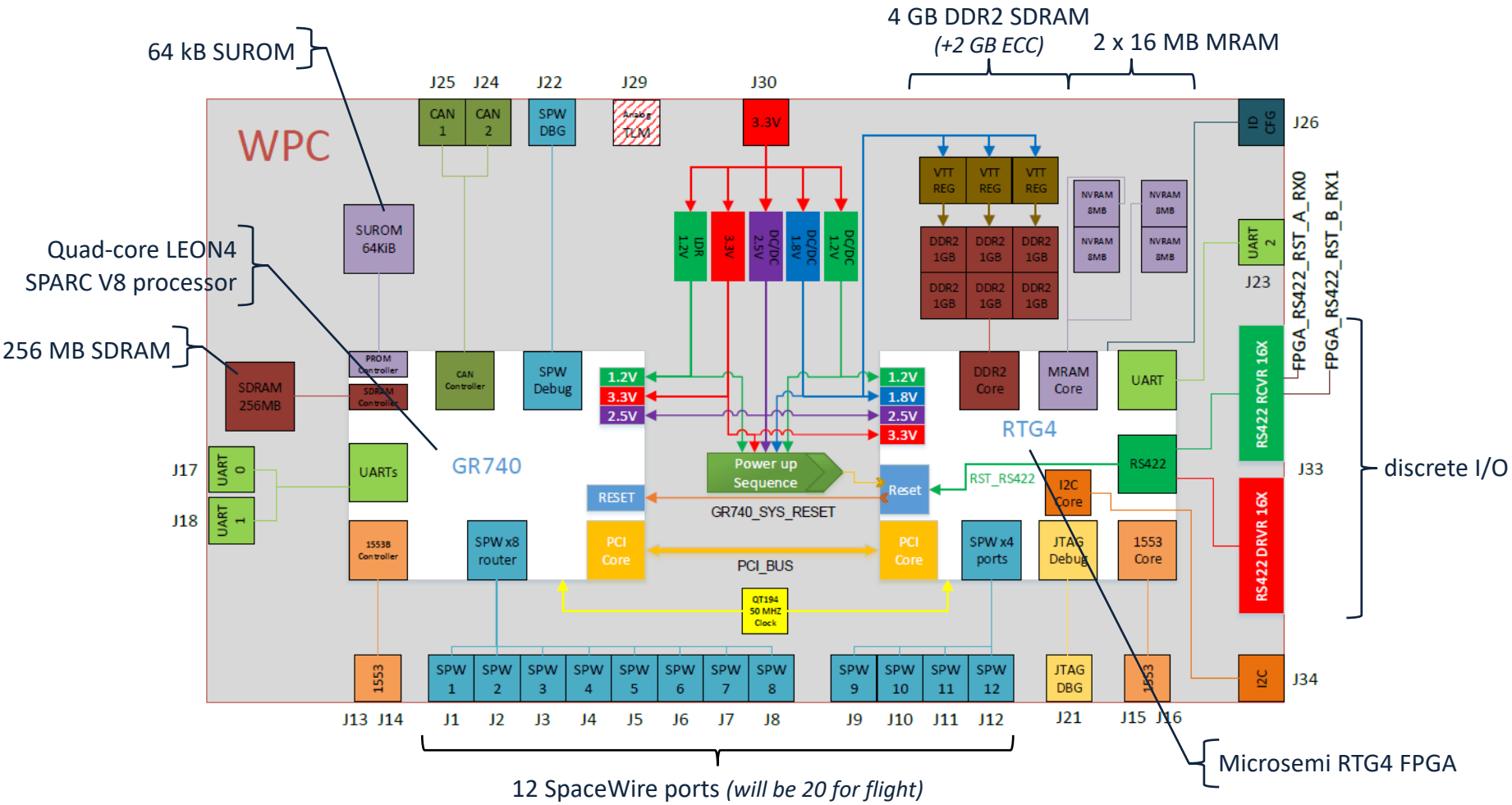
CGI processing hardware: WPC

CGI has two processing cards: ICDH and SSP

- **Both are copies of WFIRST Processing Card (WPC), which is GSFC-delivered and is replicated across WFI and the spacecraft**

- **WPC has:**
  - A GR740 LEON4 processor from Cobham-Gaisler
    - Rad-hard, 32-bit architecture, 4 cores @ 250MHz apiece
    - LINPACK puts it at 23Mflop per core for matrix operations
    - 256MB of DDR SDRAM attached locally
  - An RTG4 FPGA from Microsemi
    - Provides access to 4GB of error-corrected DDR SDRAM for large volatile memory needs
    - Provides access to 32MB of MRAM for flight software storage
  - A 33 MHz PCI bus between the two
  - Up to 20 Spacewire ports (along with several others we may or may not use, e.g. RS-422 to power slice)

WPC



Goddard-supplied WFIRST Processor Card is the platform for the SSP slice

CGI processing hardware: SSP + ICDH

SSP is a dedicated processor for high-order wavefront sensing and control.

- **Runs computationally intensive algorithms without the ICDH multitasking concerns**
  - Message-passing between SSP and ICDH will be used to get information to and from cameras and mechanisms
  - Independent connection to CGI solid-state recorder (SSR) so transfer of large stored data items does not bog down ICDH

- **Will use remaining RTG4 resources for "Fourier Optics Engine"**
  - FPGA-based single-precision 2D Fourier transform and complex elementwise mask multiply
  - Can do full FT and multiply in < 0.252 for matrices of any size up to 1739x1739
  - Can be chained together to do one operation after another, up to 9 (TBR)
  - Used primarily for calculations for high-order wavefront control, but also usable for other operations requiring Fourier transform capability (use a mask of all ones for FT only). Available but not a requirement.

ICDH handles interfaces with spacecraft and with electronics controlling mechanisms and cameras. It will pass messages and telemetry, and run small control loops.

- **Not suitable for heavy computation; it has too many other responsibilities**

CGI processing hardware: other

SSR will be a solid-state recorder of at least 60GB

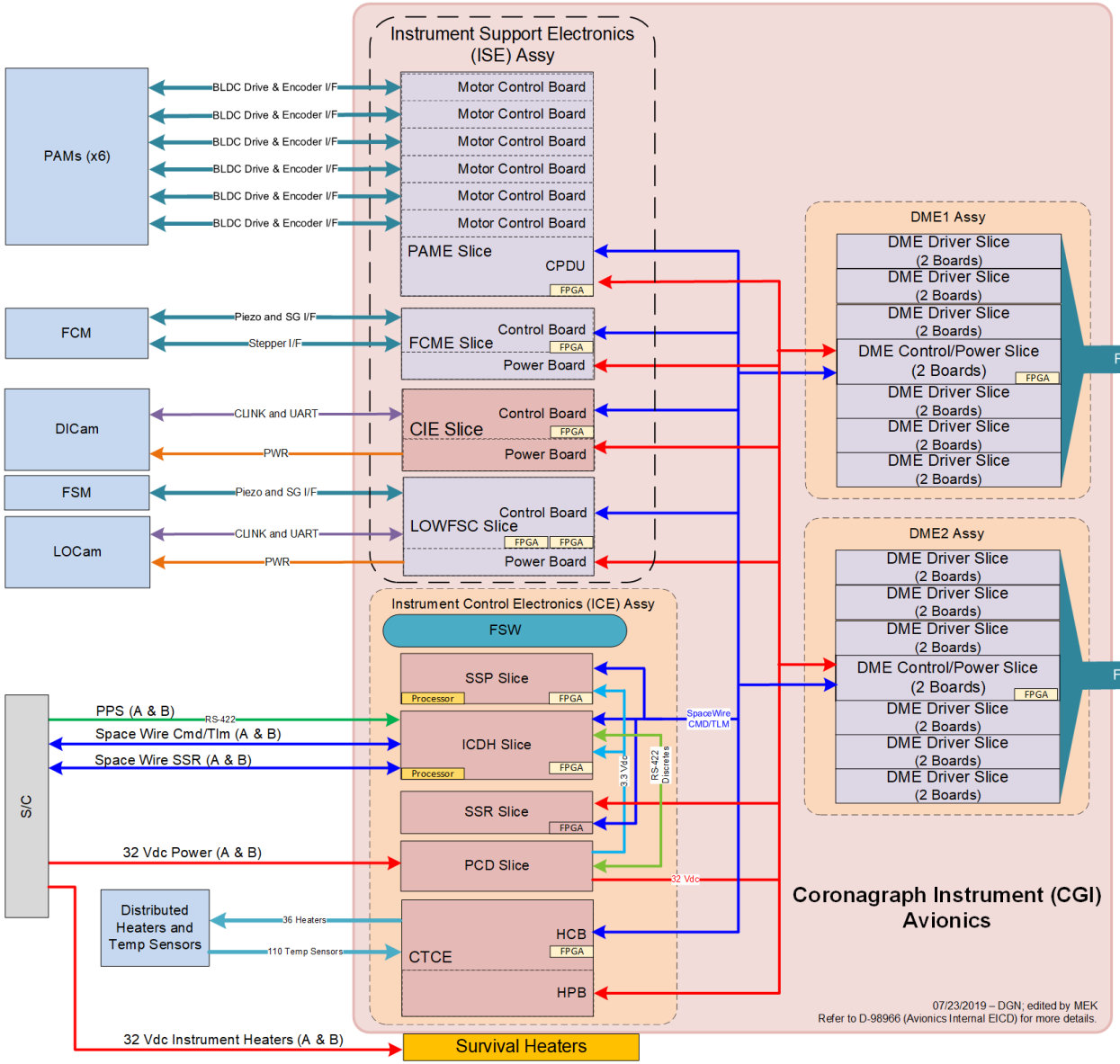
- Suitable for long-term storage of large data items (calibration data, wavefront control Jacobians, etc.)
- Will have dual-port access to ICDH, so either can talk to it independently
- Finite (but large) number of writes permitted
- To be purchased from vendor

CGI will also have several other JPL-produced "slices", boards dedicated for control of particular hardware:

- PCD for power
- CTCE for thermal
- PAME for Precision Alignment Mechanisms (PAMs), the x-y stages holding masks
- LOWFSC slice for the Fast Steering Mirror (FSM), the low-order camera (LOCAM), and all the low-order estimation and control between those two.
- FCME for the Focus Control Mechanism (FCM)
- DME slices for deformable mirror (DM) control
- CIE for interfacing with the EXoplanetary systems CAMera (EXCAM)

Both cameras also have vendor-sourced proximity electronics directly connected to the camera itself.

Avionics block diagram



Legend:

- Tested together before delivery to ETB and II&T
- Delivered separately to users before integration in ETB and II&T

List of Abbreviations:

- CIE = Camera Interface Electronics
- CTCE = Coronagraph Thermal Control Electronics
- CPDU = Command & Power Distribution Unit
- DICam = Direct Imaging Camera
- DM = Deformable Mirror
- DME = Deformable Mirror Electronics
- FCM = Focus Control Mechanism
- FCME = Focus Control Mechanism Electronics
- FSM = Fast Steering Mirror
- FSW = Flight Software
- HCB = Heater Control Board
- HPB = Heater Power Board
- ICDH = Instrument Command & Data Handling (GSFC WPC)
- LOCam = Low-Order Wavefront Sensor Camera
- LOWFSC = Low Order Wavefront Sensing & Control
- PAM = Precision Alignment Mechanism
- PAME = Precision Alignment Mechanisms Electronics
- PCD = Power Conditioning & Distribution
- SSP = Starlight Suppression Processor (GSFC WPC)
- SSR = Solid State Recorder

CGI telemetry

CGI will send down almost every piece of data it collects on the high-rate link:

- **All EXCAM images**
- **All commanded DM settings (both high-level WFSC-commanded and 16-bit exact DAC settings)**
- **All final encoder positions of mechanisms after moves**
- **All calibration products**
- **All electric field estimates**
- **All LOWFS estimator products being sent to any of the low-order control loops (line-of-sight, focus, Zernike)**
- **All spacecraft reaction-wheel speed and torque data received from the WFIRST ACS to CGI for line-of-sight control**
- **Response codes from every completed algorithm**
- **A regular telemetry output of all temperatures and voltages within CGI**
- **All LOCAM images, summed up to once every 10 seconds**
  - If we'd output the raw 1kHz output, it would driven our implementation and busted our data rate requirements.

These should be available no later than 72 hours after collection.

A subset of this will be sent on the housekeeping link for near-real-time observer access.

CGI data rate

L3 CGI - CGI Maximum High Rate Data Bus Data Volume

The CGI shall not transfer more than 3 Tbits over any 24 hour period to the spacecraft on the high rate data bus.

L3 CGI - CGI Maximum Data Rate Allocation

The CGI shall remain within a maximum data rate to the SSR of 60Mbps.

	Requirement	CBE	Margin
Data Rate	60 Mbps	10.2 Mbps	83%
Data Volume	3 Terabits/day	0.88 Terabits/day	71%

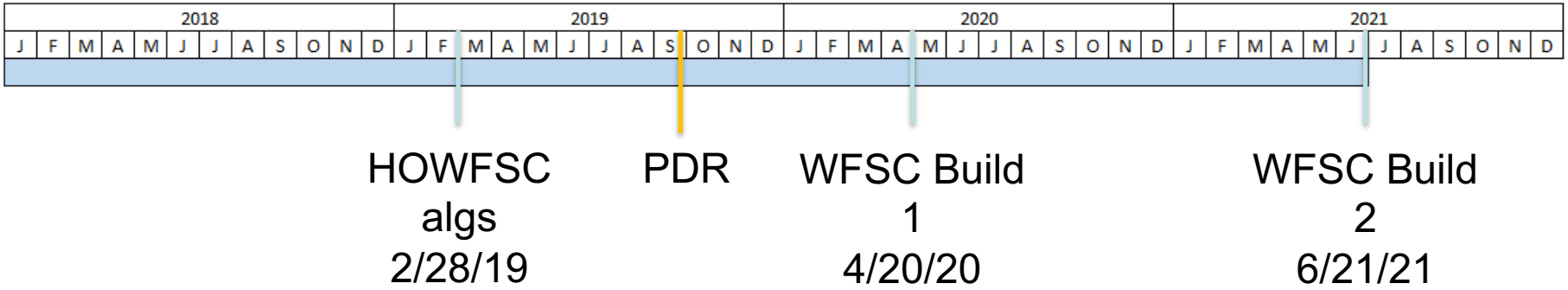
Some room on data volume if needed.

CGI HOWFSC software scope

Current HOWFSC baseline:

- **Pairwise probing for wavefront estimation**
  - Pairs of DM settings modulate the starlight, and images of these are combined with a system model to extract amplitude and phase
- **Electric-field conjugation for wavefront control**
  - Basically a weighted least-squares fit, with regularization
    - Uses a DM Jacobian, a model-based representation of the change in electric field from moving each actuator
    - Do an Ax = b solve to back out the next DM setting given the estimated E-field
    - Many parameters to tune it (weights, regularization schedules vs. iteration, size of region being controlled…)
  - Requires careful precalibration to avoid model mismatch
- **Phase retrieval for wavefront estimation during precalibration**
  - Use 6 lenses on DPAM (imaging lens, pupil lens, 4 weak lenses) to introduce diversity
  - Estimates pupil-plane phase using parametric fitting for low-order aberrations and modified Gerchberg-Saxton for higher-spatial-frequency aberrations
- **Other algorithms for cleaning images, aligning masks, doing WFSC astrometry/photometry/plate scale calcs…**

CGI HOWFSC software schedule



Next delivery: end-to-end WFSC in April 2020 to FSW

- All remaining LOWFS and calibration
- Any HOWFSC updates since Feb 2019
- Very few missing pieces at present; biggest gaps are automation of calibration routines which were previously operator-in-the-loop
- Focus is on delivering a complete, working baseline

Build 2 (June 2021):

- incorporate any feedback from FSW implementation of Build 1
- Possible opportunity for algorithm updates with some WFSC support

After Build 2: WFSC will be wrapped up and personnel moved elsewhere within CGI (I&T, Testbed, SE, …); supporting external contributions will be harder

Path to CGI behavior updates

Four paths to updating CGI behavior (from easiest to hardest):

1. **Re-ordered commands**
   - CGI will have a command dictionary which gives a list of all knobs available for an operator to turn
     - Most will be low-level hooks to move mechanisms, open/close loops, take images, etc.
     - A handful will be "flight software behaviors", which string together low-level behaviors with processing activities and data passing to create integrated functions which can also be called as commands. Examples:
       - align a pupil-plane mask
       - compute plate scale for one or more filters
       - run the CGI baseline HOWFSC loop
   - CGI will operate on sequences of commands strung together
     - Very limited ability to pass information between them, however
   - If a new CGI behavior can be assembled from a sequence of existing commands, it could be accommodated with essentially no extra work
     - Example: rotating satellite spots during a blind-search observation, to keep an star-centration reference while providing full coverage

Path to CGI behavior updates

Four paths to updating CGI behavior (from easiest to hardest):

2. **Updating parameters and stored data**
   - CGI will use stored configuration data to define parameters for calibration and wavefront control routines
     - WFSC-relevant examples:
       - regularization parameter schedules
       - per-pixel and per-actuator weighting matrices
       - region of interest for control ("dark hole" location)
       - DM probe shapes, locations, and magnitudes
       - combinations of subfilter and star off-axis offset to use for control ("control channels")
     - Other parameters include control-loop parameters, alignment tolerances for iterative routines, etc. Can include parameters in FPGAs.
   - Behavior changes that can be done by updating parameters within the existing CGI framework are the next easiest to do
     - Example: changing the control region of interest to dig a smaller (but ideally deeper) dark hole on one side of the PSF
     - Example: changing the regularization schedule to correct more aggressively more often if the calibration supports it

Path to CGI behavior updates

Four paths to updating CGI behavior (from easiest to hardest):

3. **Updating flight software (FSW)**
   - JPL Design Principles 4.1.7.3: "**Capability to modify flight software** - The design shall include the capability to modify flight software of spacecraft components containing reprogrammable flight software in-flight through the C&DH subsystem via the uplink command function, or prior to launch via the umbilical link."
     - At JPL, Design Principles (with "shall") must be adhered to unless a waiver is explicitly granted. We are not planning a waiver on this that I am aware of.
     - This only applies to "reprogrammable" flight software, so SSP/ICDH yes, FPGAs no.
   - So yes, we can update any of the CGI FSW at any point, even after launch. But the procedure to do so is much more involved than the first two.
     - Expect it to be a much slower process (see next slide)…

Path to CGI behavior updates

- **Code must be written (C/C++ for VxWorks) with tests**
- **Code must go through software quality checkout and regression testing, and be tested on the ground-based instrument testbed to verify it**
  1. works as expected
  2. doesn't break the instrument
  3. doesn't break any of the existing software functionality
- **Documentation must be updated (e.g. command dictionary, design doc, user guides)**
- **There will be a Software Review and Certification Record (SRCR); this review must be completed to transfer the code from the development team to the operations team who will upload it**
- **If the FSW change is introducing a new command, Ground System and possibly spacecraft software must be updated as well to handle the new command, with their own testing**
- **And anecdotally, expect to meet resistance from many stakeholders**
  – A FSW update could brick an otherwise working instrument, and nobody wants a piece of that one…

<u>None of these are impossible to overcome</u>, but be aware it will cost time and money to get through them all

Path to CGI behavior updates

Four paths to updating CGI behavior (from easiest to hardest):

4. **Updating FPGA behavior/electrical-hardware configuration**
   - Not possible after launch
   - Nearly impossible after start of II&T (enormous standing-army cost, likely only to happen if something is genuinely broken and not caught earlier)
   - Should not really happen after Critical Design Review (CDR) in Nov. 2020
     - Presenting detailed design and design validation at this gate, ready to start implementation
   - For existing FPGAs, will be limited by the needs of other CGI activities that already use the resources on a part
   - Will be competing for resources (budget, engineer time) with existing CGI activities
   - Technically possible, but really very disfavored unless it's an immediate change that helps CGI meet its existing requirements with more margin or lower cost