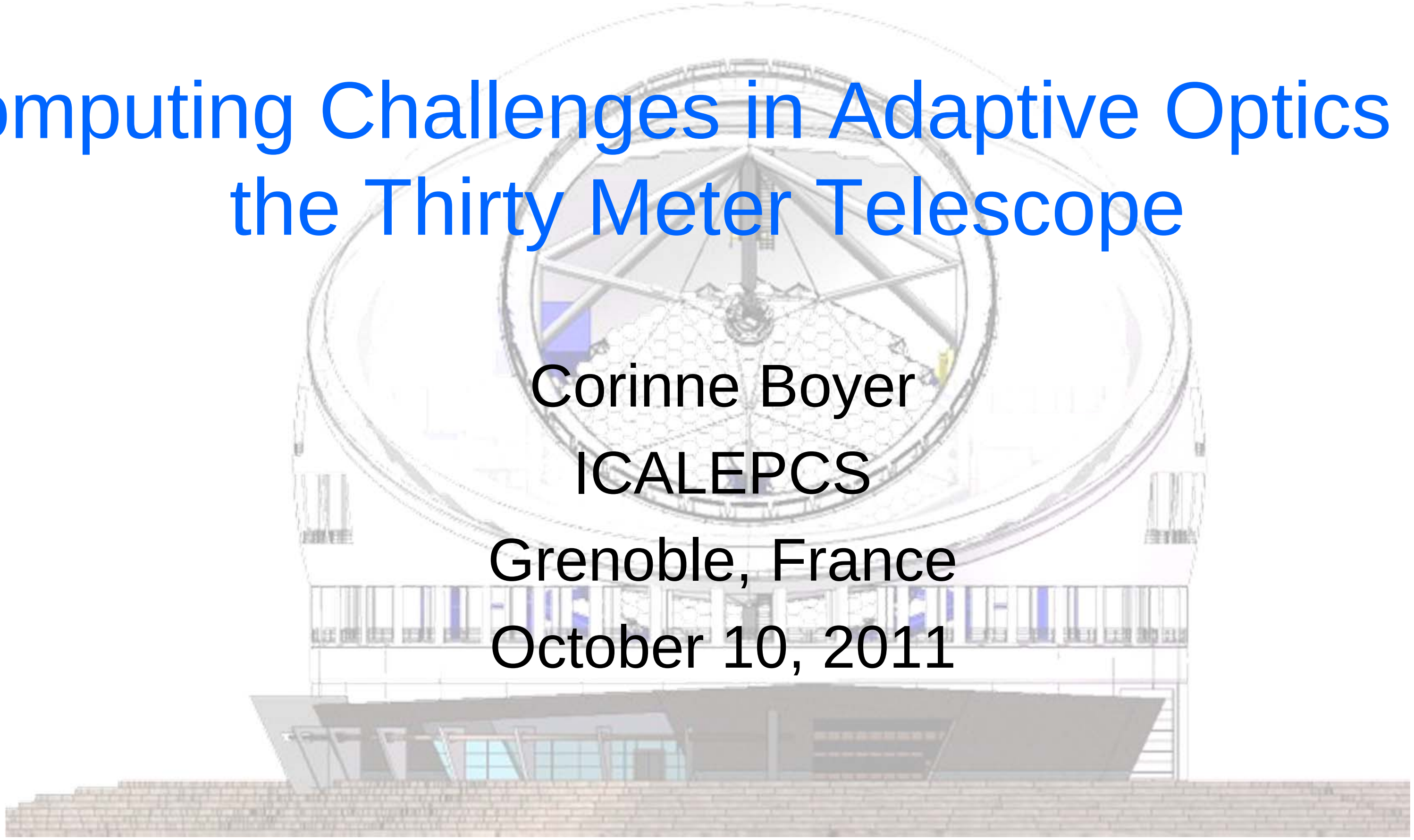
THIRTY METER TELESCOPE

Computing Challenges in Adaptive Optics for the Thirty Meter Telescope



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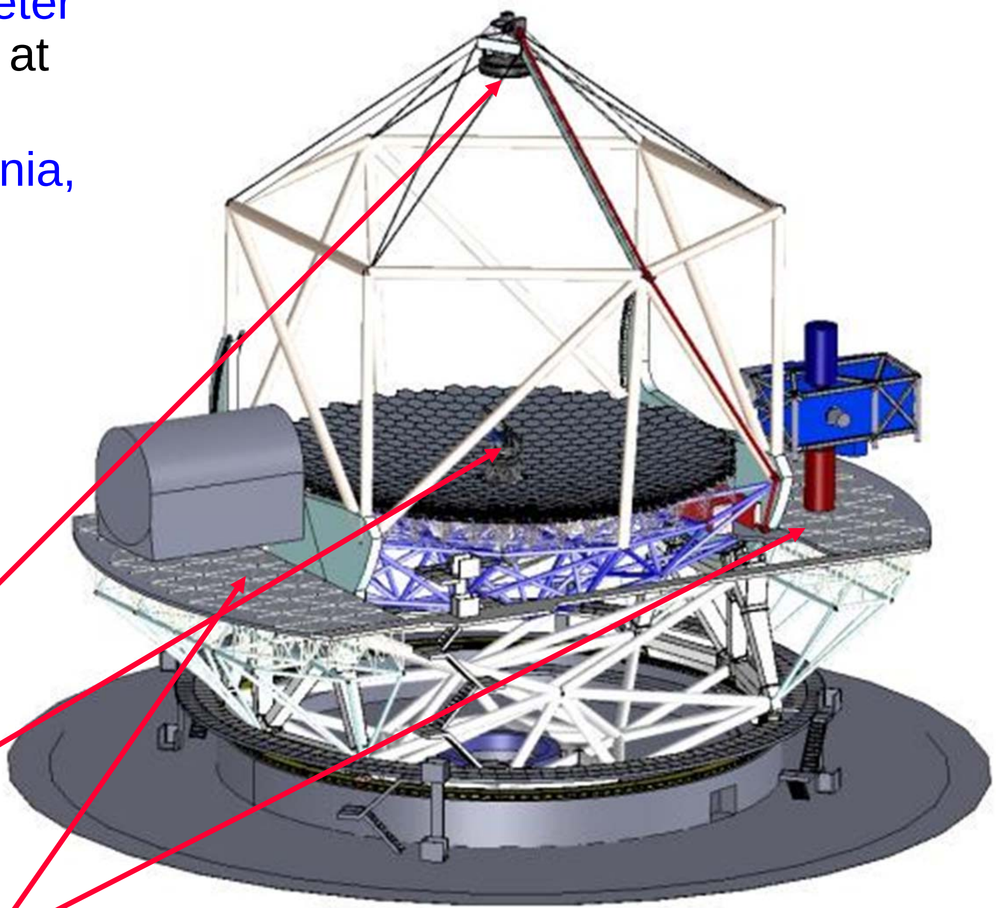
This Talk

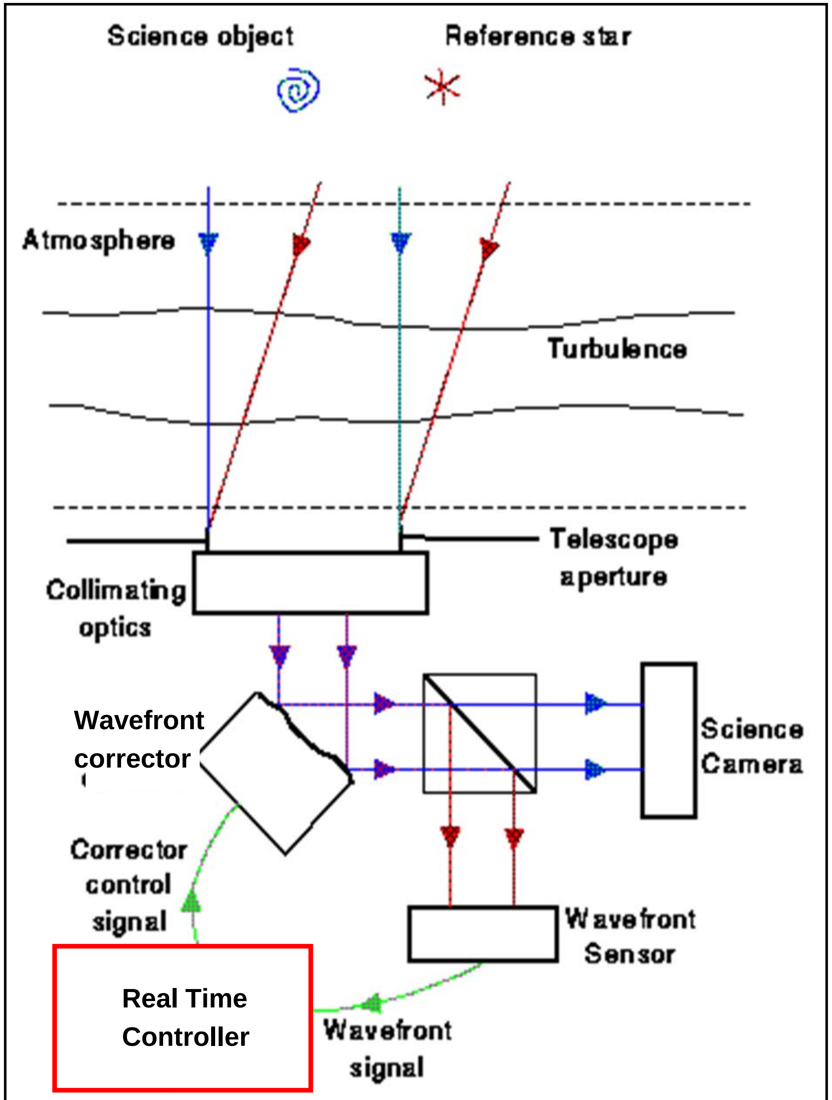
- Introduction to the Thirty Meter Telescope (TMT)
- Adaptive Optics (AO) Basics
- TMT first light AO system
  - System architecture
  - Computing challenges
  - Control Algorithms
  - Conceptual Designs
- Next steps and future TMT AO challenges

Thirty Meter Telescope Overview

- Design, build and operate a thirty meter telescope for research in astronomy at optical and infrared wavelengths
- Collaboration of University of California, Caltech, ACURA (Canada), NAOJ (Japan), the Department of Science and Technology of India, and the NAOC (China)
- Mauna Kea in Hawaii
- Ritchey-Chrétien optical design
- 30 m segmented aperture
  - 492 segments
- 3.1 m convex active secondary
- Articulated tertiary
  - Flat elliptical, 2.5m x 3.5m
- 20 arc min FOV (15 unvignetted)
- Nasmyth-mounted instrumentation



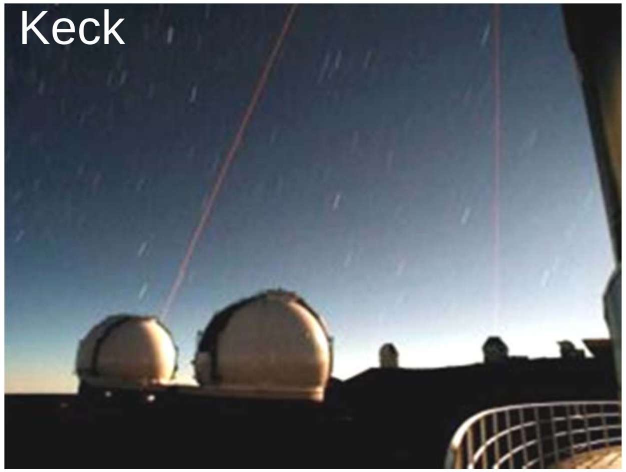
Adaptive Optics (AO) Increases Telescope Sensitivity



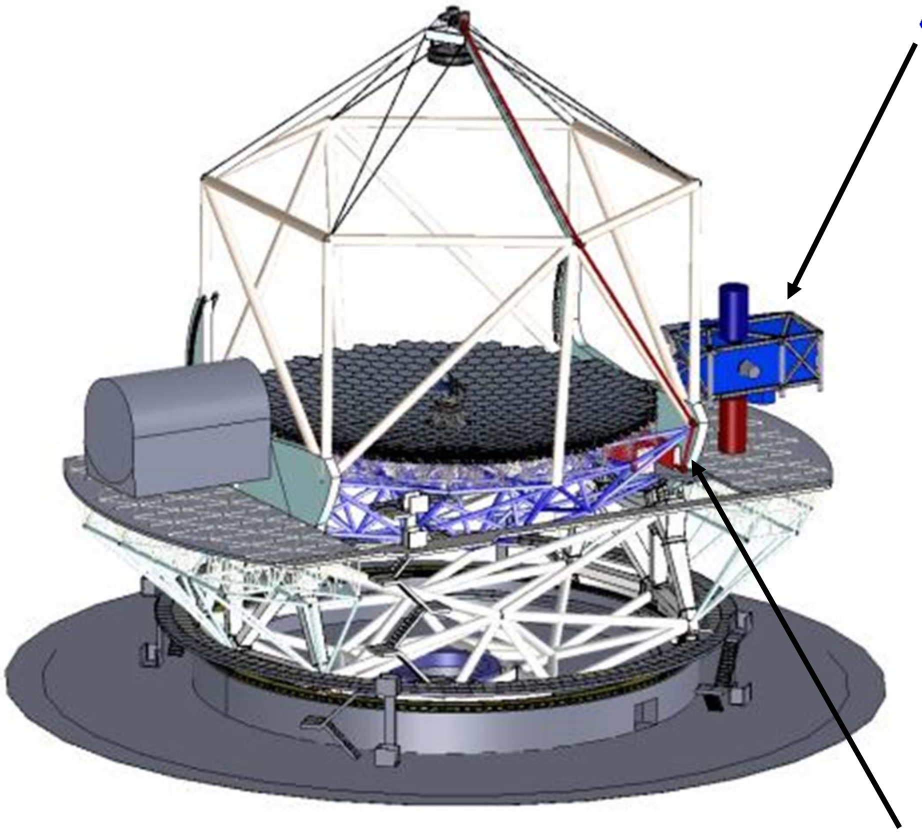
- Performance of ground-based telescopes are limited by atmospheric turbulence
- AO Systems allow the removal in real time of the effect of atmospheric turbulence
- How it works:
  - Wavefront distortions are measured with a wavefront sensor (WFS)
  - Then corrected by a wavefront corrector or deformable mirror (DM)
  - Optimal shape of the DM are computed by a Real Time Controller (RTC) with simple matrix-vector multiply
  - Need a bright reference star nearby
  - Natural Guide Star (NGS) AO
  - Two limitations: poor sky coverage and small corrected field of view

Laser Guide Star Adaptive Optics (LGS AO)

- Sky coverage is increased by using artificial reference stars (Laser Guide Stars) generated by laser beams
  - Still some limitations:
    - Finite range of LGS induces a "cone effect"
      - Constellation of guide stars allow to estimate 3-d turbulence profile (using tomographic algorithms) and turbulence can be compensated in 3-d using multiple deformable mirrors: Multi Conjugate Adaptive Optics (MCAO)
    - Natural guide stars still required (but much fainter) for tip/tilt and focus correction

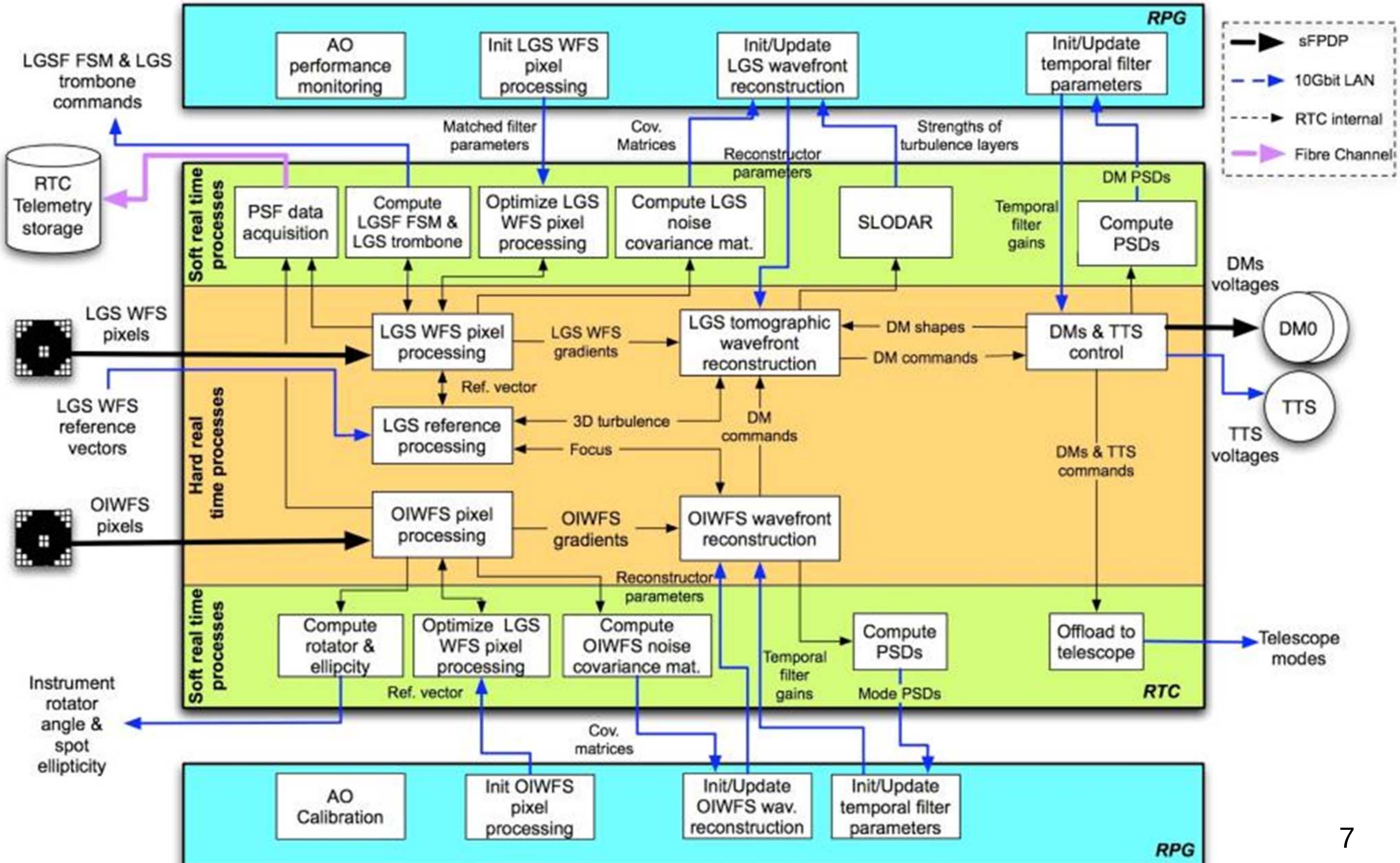


The TMT First Light AO architecture

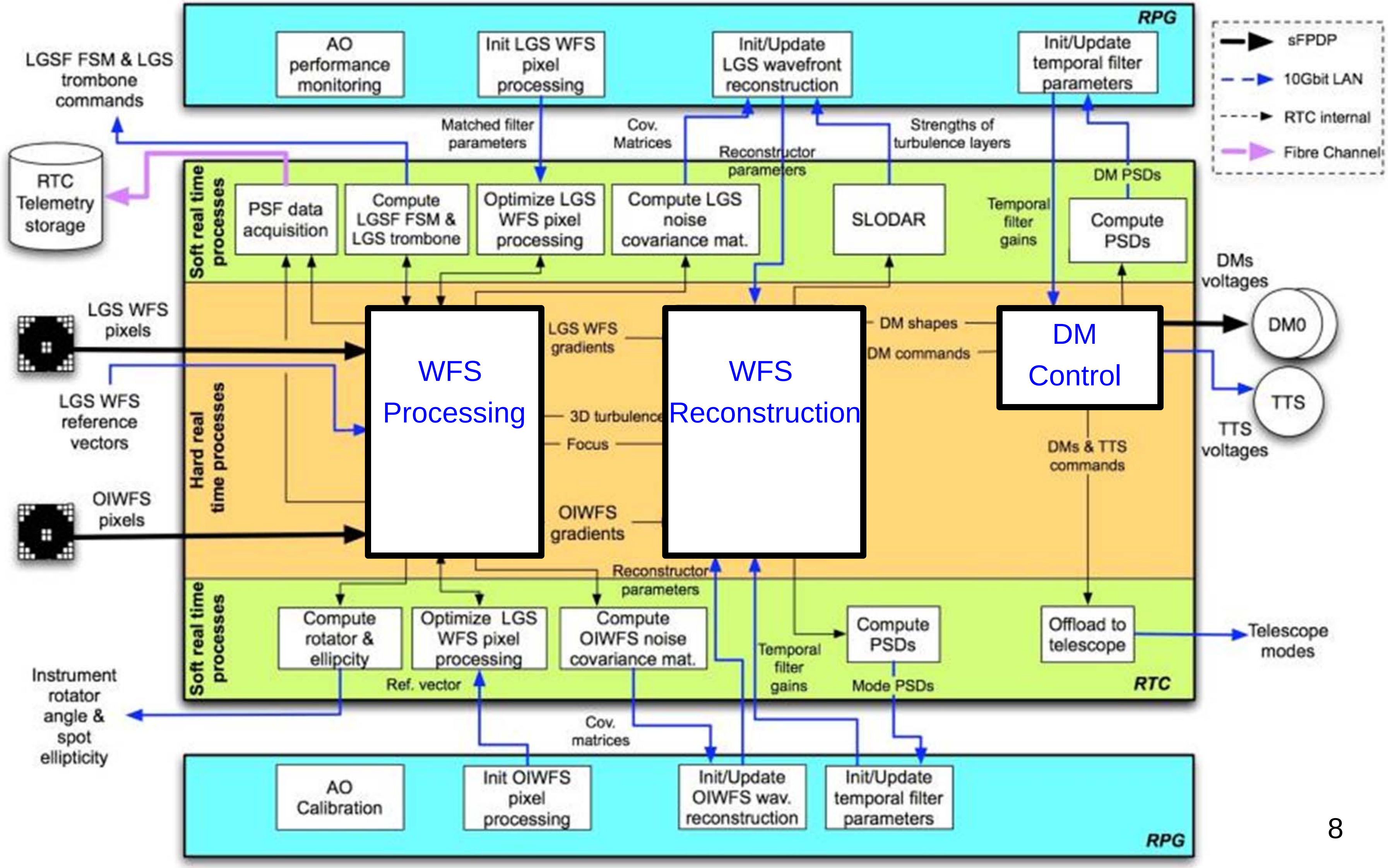


- MCAO LGS System:
  - Six LGS WFS and three low-order NGS WFS (~1.2M pixels, ~35K gradients)
  - Two DMs with ~8000 actuators
  - One Real Time Controller solving a 35k x 8k control problem at 800Hz with 1000μs end-to-end latency:
    - Size of problem at least 2 orders of magnitude greater than most challenging AO systems in operation
- Laser Guide Star Facility:
  - Generates up to 9 LGS

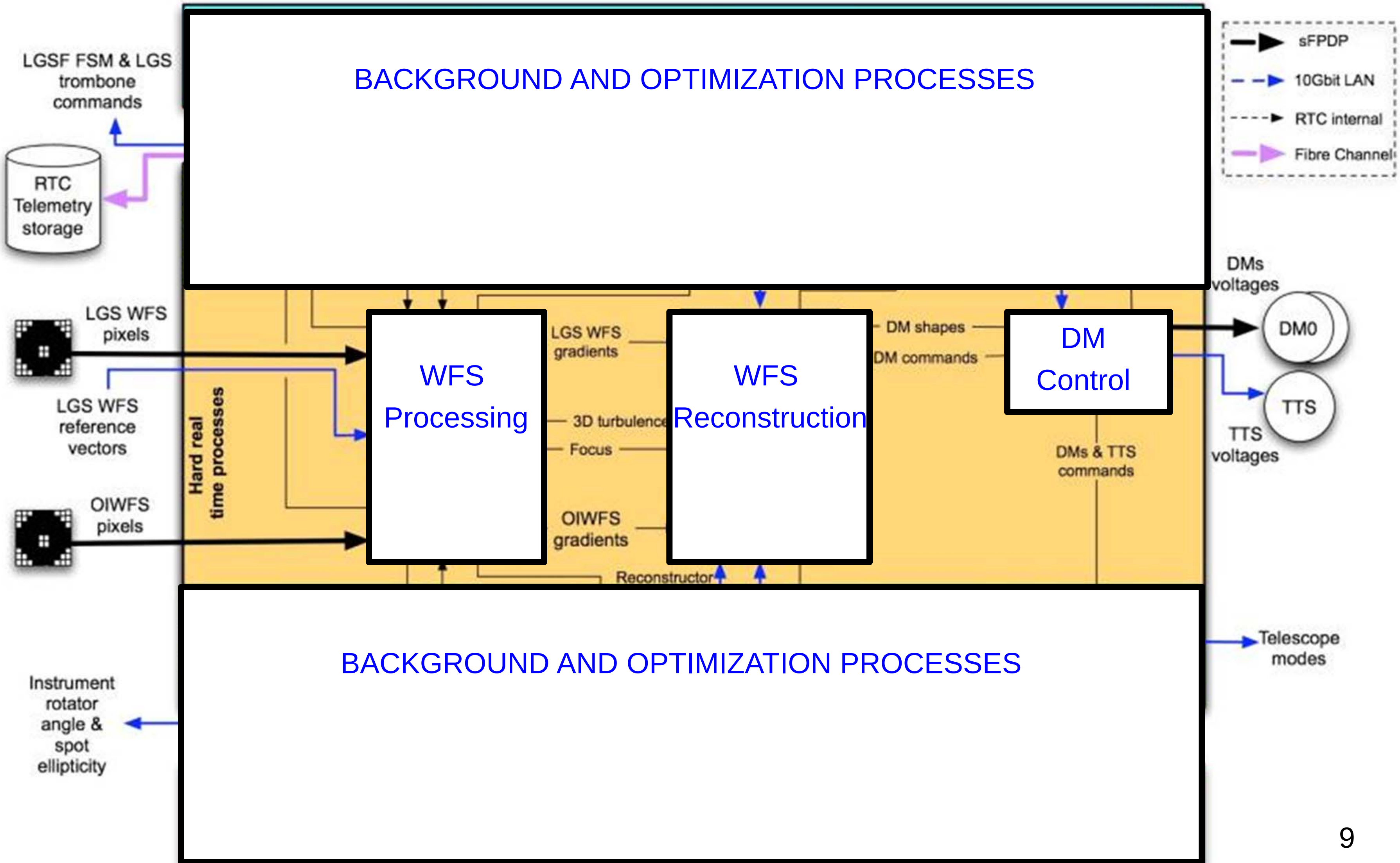
TMT First Light AO LGS Real Time Computing Block Diagram



TMT First Light AO LGS Real Time Computing Block Diagram



TMT First Light AO LGS Real Time Computing Block Diagram



Wavefront Reconstruction

- Wavefront reconstruction consists of two steps:
  - 3-D turbulence profile estimated with tomographic algorithm
  - Projection to various DM with DM fitting algorithm
- Minimum variance algorithms to solve both steps
  - Conventional matrix-vector multiply approach impractical on account of memory requirement and need to update the algorithm in real time
  - Computationally efficient algorithms and innovative hardware implementations needed
- NGS wavefront reconstruction is performed separately using standard modal least-square reconstructor:
  - Split tomography
    - Better control of low-order modes
    - Reduce coupling between LGS and NGS modes

LGS Tomography (1)

- Minimum variance algorithm:

$$\underbrace{\left(G^T C_N^{-1} G + C_X^{-1}\right)}_{A} x = \underbrace{G^T C_N^{-1} s}_{b} \quad \text{with} \quad \begin{cases} s = Gx + n \\ C_X = \left\langle xx^T \right\rangle \\ C_N = \left\langle nn^T \right\rangle \end{cases}$$

- System to solve has the form A x = b
  - A is the block-structured tomography operator (sparse and low-rank)
  - x is the tomography vector of unknowns (OPD)
  - b is the right hand side tomography vector computed from the pseudo open loop LGS gradients
- Several options have been developed for the tomography step as alternatives to the standard (and impractical) matrix-vector-multiply solution
  - Iterative solutions
  - Grid-based computations
  - Warm restart used to accelerate convergence
  - For all solutions, study impact on AO performance
- Solvers perform matrix-vector multiplications

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LGS Tomography (2)

- 2 System-oriented solvers:
  - CG30: 30 iterations of Conjugate Gradient (no preconditioning) operating on the whole tomography system
  - FD3: 3 iterations of Fourier Domain Preconditioned Conjugate Gradient operating on the whole tomography system
- 2 Layer-oriented solvers (block generalization of the Gauss-Seidel iteration):
  - BGS-CG20: Block Gauss-Seidel with 20 iterations of Conjugate Gradient for each atmospheric layer
  - BGS-CBS: Block Gauss-Seidel with Cholesky back-substitutions for each atmospheric layer

DM Fitting

- DM fitting matrix system has also the form A x =b
  - A is the block-structured fitting operator (sparse)
  - x is the DM actuator vector of unknowns
  - b is the fitting right hand side vector
- Proposed solver: 4 iterations of Conjugate Gradient (CG4).

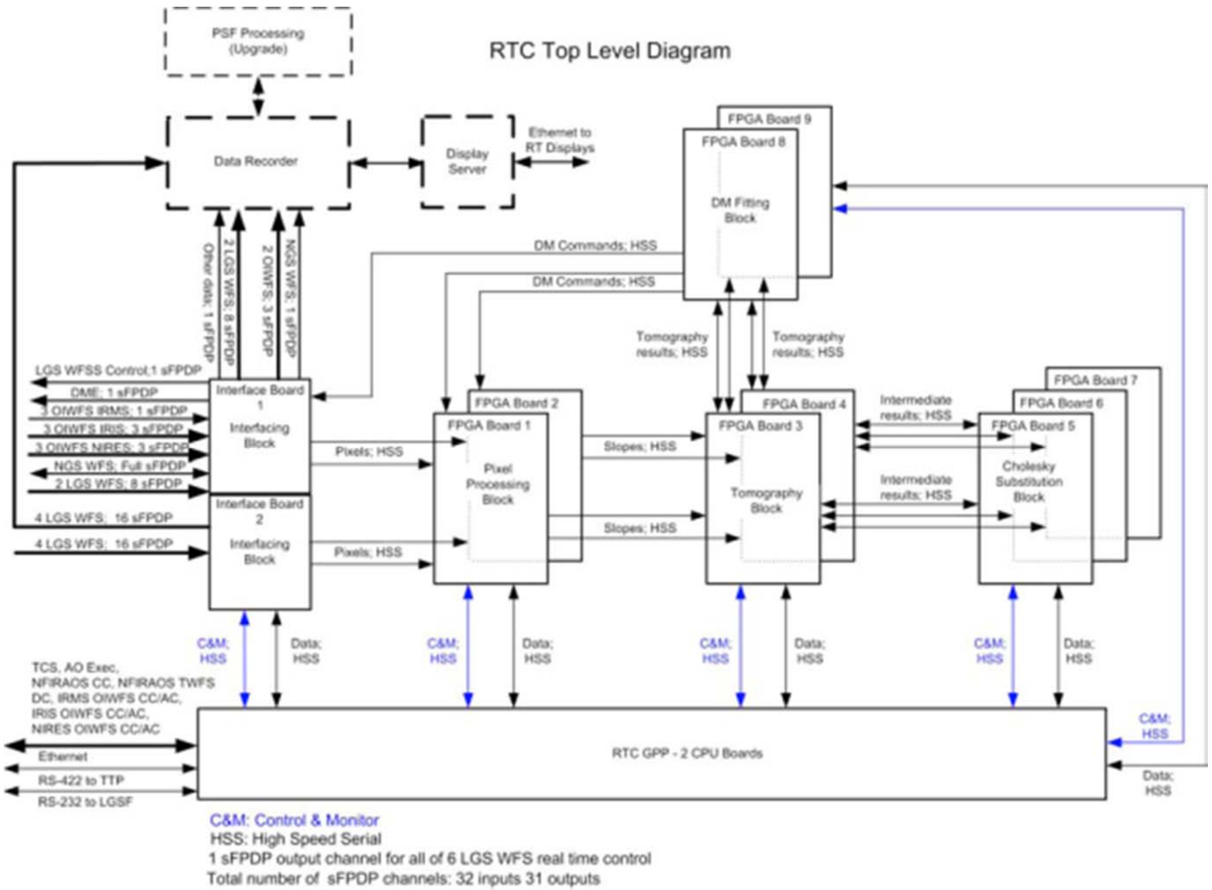
Computation and Memory Requirements

	Memory (MB)	**Number of operations GMAC/s (1000μs latency)**
LGS WFS processing	10	7.2
LGS wavefront reconstruction		
BGS-CBS	50	80
BGS-CG20	2	280
CG30	2	245
FD3 (2 layers oversampled)	10	140

Hardware Implementation

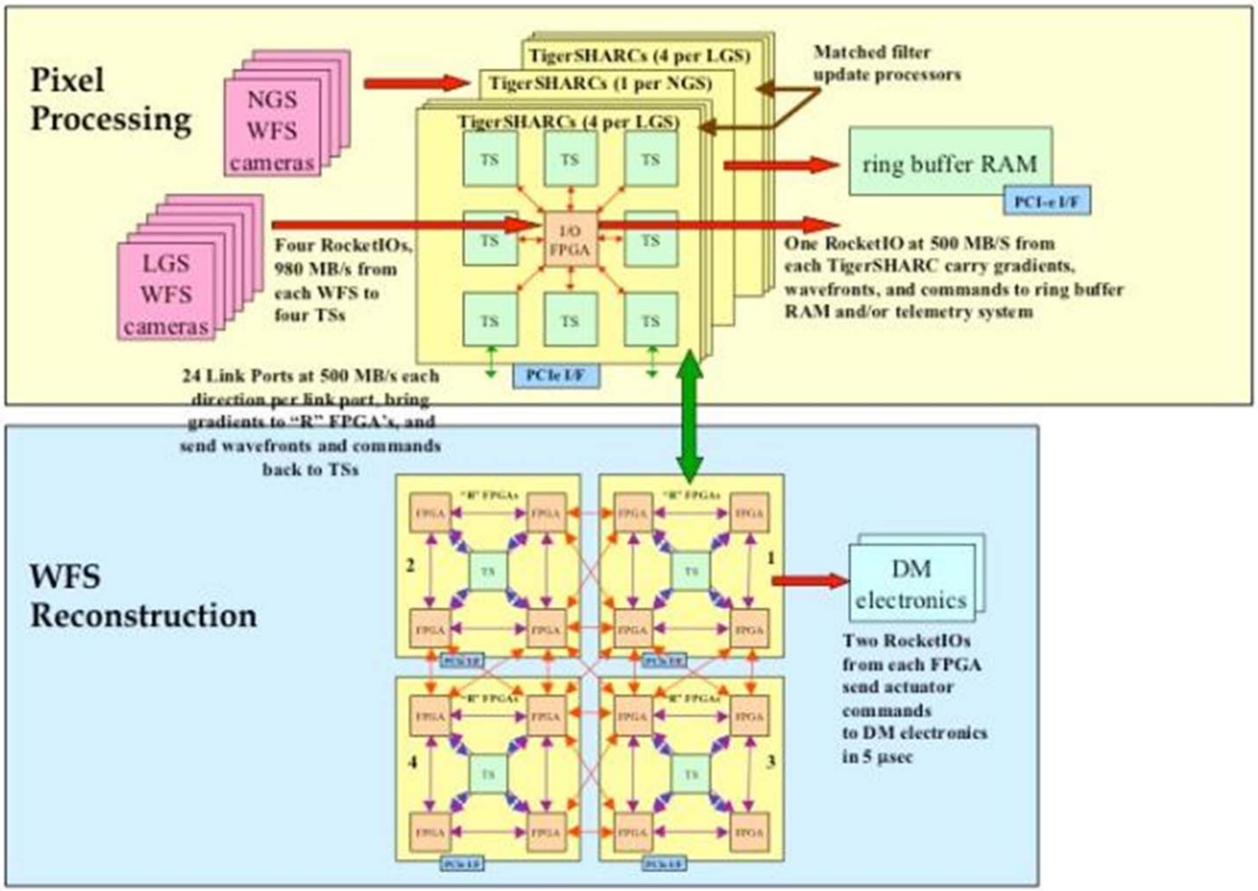
- TMT has supported two competitive studies for the conceptual design of the first light TMT AO system real time controller:
  - DRAO (Dominion Radio Astrophysical Observatory) and tOSC (the Optical Science Company)
  - Both companies have demonstrated the feasibility of developing the TMT real time controller using Xilinx's Virtex-5 FPGA technology.
- Hardware architecture depends upon choice of tomographic algorithm
  - Which impacts processing requirement and memory requirement
- Hardware implementation impacts the latency
  - Appropriate processor for each task (Field Programmable Gate Arrays, Digital Signal Processor, Graphic Processing Unit, others…)
    - Floating point versus fixed point
  - Parallelization efficiency including inter-processor communication and bus contingencies
  - On-chip memory is limited
    - Multiply the number of processors
    - Add external memory

DRAO Conceptual Design Study



- 9 custom FPGA boards including 6 Xilinx Virtex-5
- 2 custom interface boards with 32 sFPDP full duplex links
- 2 general purpose computer boards
- Mounted in ATCA chassis
- Highly modular architecture
  - Fixed-point operation
  - BGS-CBS algorithm

tOSC Conceptual Design Study



- 7 custom TigerSHARC cluster boards (8 TigerSHARC and 1 Xilinx Virtex-5 FPGA)
- 4 custom FPGA cluster boards (4 Xilinx Virtex-5 FPGA and 1 TigerSHARC)
- One Ring Buffer board
- One general purpose computer board
- Mounted in ATCA chassis
- Meets TMT latency goal requirements
  - Floating-point operation
  - CG algorithm

Conclusions and Future Computing Challenges for TMT

- Building the real time controller for the TMT first light AO system is the first computing challenge for TMT AO in terms of:
  - Algorithm complexity,
  - Processing requirements,
  - But is feasible with today's technology.
  - Next steps:
    - Review latest generation of processors
    - Select an algorithm and define architecture
    - Develop prototype and test key components
- Other challenges will follow:
  - Adaptive Optics Secondary: Synchronization of various real time systems
  - MCAO Upgrade: Will implement a higher order wavefront sensors and deformable mirrors requiring at least a factor 4 in processing and memory requirements
  - Multi-Object Adaptive Optics (MOAO) System may also be very challenging:
    - 8 LGS and up to 20 DMs (one per science object)


Questions?
TMT web-site: www.tmt.org