Addressing Thermal Model Run Time Concerns of the Wide Field Infrared Survey Telescope using Astrophysics Focused Telescope Assets (WFIRST-AFTA)

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Agenda

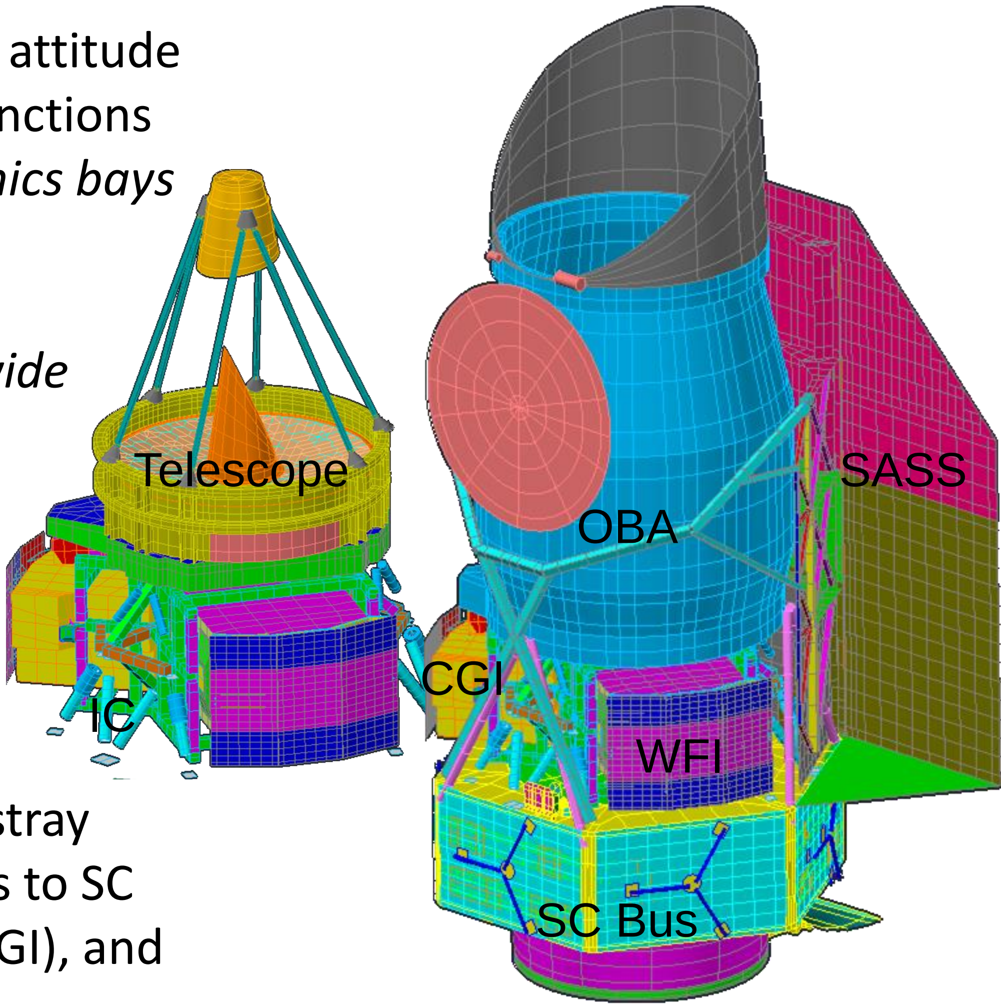
- WFIRST Mission Overview
- Overall Observatory Design
- Simulation of Survey Type Missions
- Evaluating PID Controller Behavior
- Impact of Parallel Runs on Model Runtime
- Impact of Fluid Modeling on Model Runtime
- Impact of Radiation Coupling Filtering on Model Runtime
- Conclusions and Moving Forward

WFIRST Mission Overview

- Top Ranked large scale space mission in 2010 New Worlds, New Horizons Decadal Survey for Astronomy and Astrophysics
  - *Measures Dark Energy, Exoplanet Microlensing, and the near InfraRed Sky*
- Includes a 2.4 m *existing* telescope donated from elsewhere in Federal Government
- Includes two baseline instruments supported by Instrument Carrier
  - *Wide Field Instrument (WFI) with 2 channels*
    - IR imaging with 3x6 array of H4RG detectors for a FOV about 100x Hubble's WFC3 Instrument
    - Integrating Field Channel using a slicer and spectrograph to provide individual spectra of each slice
  - *CoronaGraph Instrument (CGI)*
    - Imaging and spectroscopic modes to image exoplanets and debris discs around nearby stars

WFIRST Mission Concept Review
Observatory Design

- Orbits Earth-Sun Lagrange Point 2
- Spacecraft bus (SC Bus) provides power, attitude control, comm., and other spacecraft functions
  - *7 modular, on-orbit serviceable avionics bays*
- SC Bus Top Deck supports
  - *Instrument Carrier via 3 bipods*
  - *Solar Array Sun Shield (SASS) to provide stable thermal environment*
- Instrument Carrier (IC) supports
  - *Telescope*
  - *Wide Field Instrument (WFI)*
  - *CoronaGraph Instrument (CGI)*
  - *Instruments are serviceable on orbit*
- Outer Barrel Assembly (OBA) mitigates stray light for telescope. Supported by bipods to SC
- Joint mission by GSFC (BUS, WFI), JPL (CGI), and Industry (Telescope and WFI)

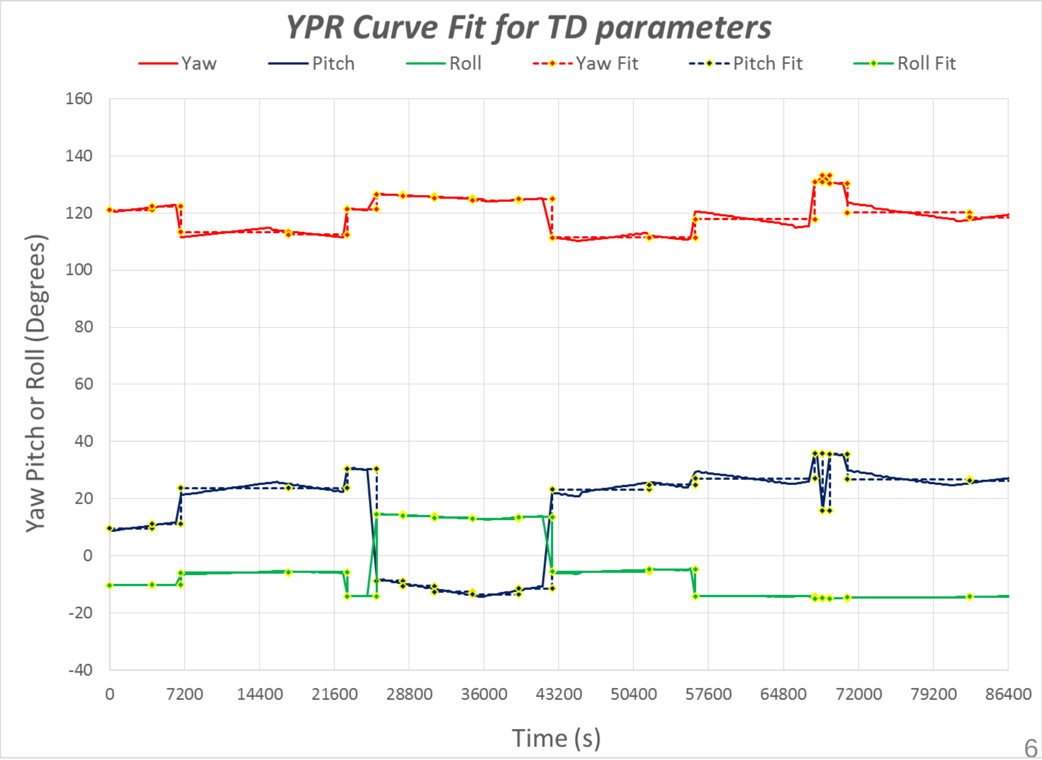


Survey Mission Simulations

- Survey type missions fall into generally one of two categories
  - *(1) Dedicated instrument with large field of view/low resolution searches for source of interest; once found, observatory slews towards source and uses second instrument with narrower field of view/higher resolution (e.g. Fermi, Swift)*
  - *(2) Surveys are planned prior to mission launch or during the mission to point at portions of the sky where known targets of interest reside (e.g. HST, JWST)*
  - *WFIRST falls into the latter category*
- Determining the worst thermal cases for survey type missions can be challenging given the large range of pointing possibilities
  - *Worst case may be at edges of Field of Regard, but not necessarily*
  - *Determining worst case slew for stability requirements is also challenging*
  - *Is worst case slew from one Field of Regard orientation to another realistic, based on the expected mission profile, especially for known target surveys?*
- WFIRST has representative pointing orientations for entire mission to ensure that all surveys can be completed in mission lifetime with allowances for guest observer time
  - *These variations and dwells may occur over short time scales*
  - *Not every slew is thermally significant. How can key changes be identified?*

Survey Mission Simulations

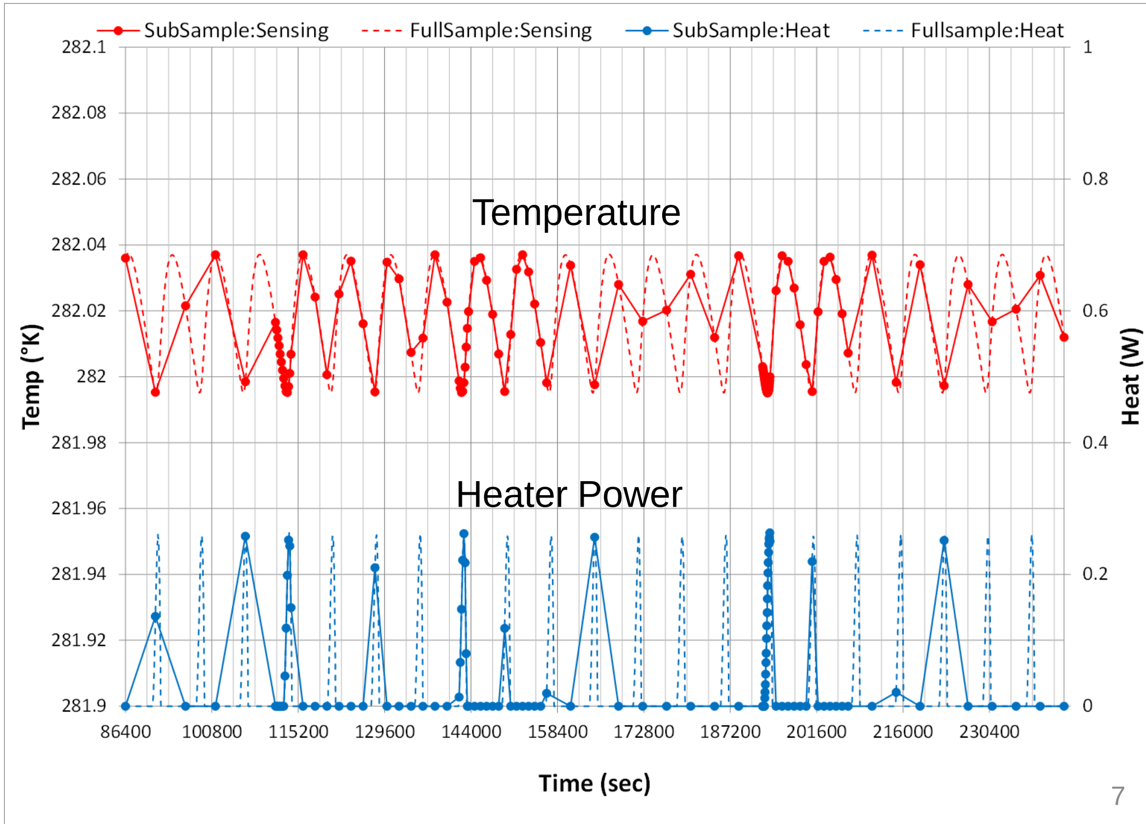
- The entire sequence of pointings for WFIRST was studied by the systems engineering team to seek a single 24 hour period which featured frequent and extreme slews as a “Day-in-the-Life” analysis case
- This resulted in 388 slews on approximately a 4 minute cadence. This was deemed to be too many points to recalculate the thermal environment each time
- Need to identify significant changes
  - Initially tried to use angle between sun vector for subsequent points (dot product). Did not account for sign…
  - Used variation in vector component
  - Average X, Y, and Z component of normalized vector to sun since last calculation point computed
  - When any parameter deviated by more than 10% since last calculation point, significant change identified
  - 36 Calculation points identified



Evaluating PID Controller Behavior

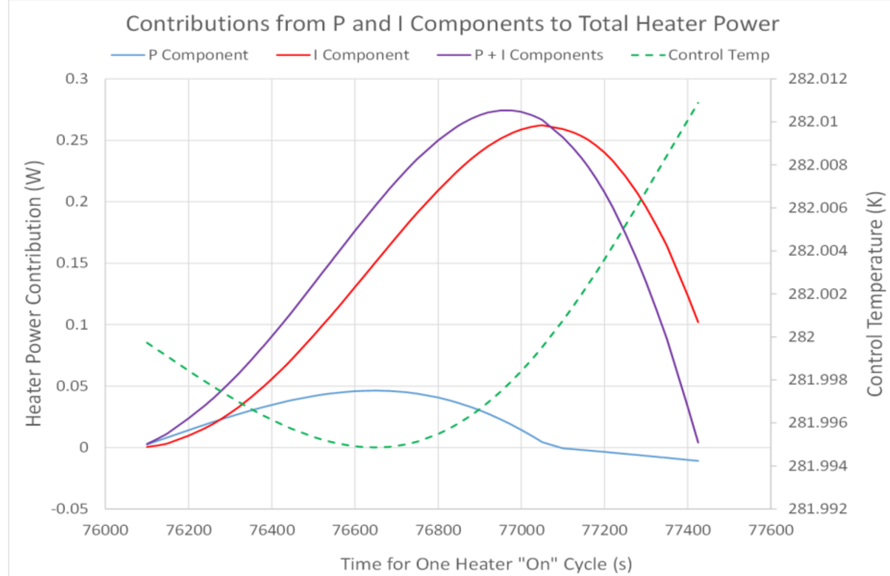
- WFIRST has a number of PID or PI heater controllers to meet stability requirements
- Predicts for one controller showed apparently poor control.
  - In actuality, the non-uniform output sampling frequency was misleading
- Even with uniform output frequency, the stability requirements were still not met

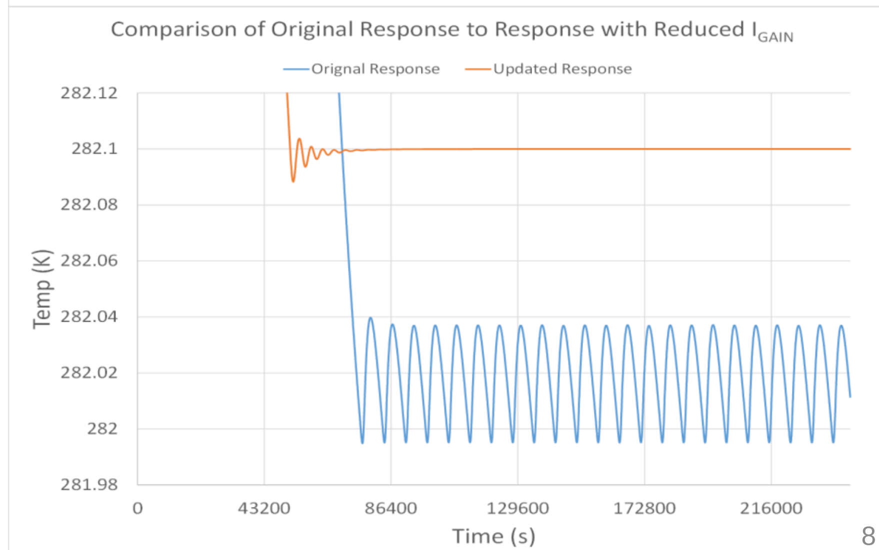
- $Q_{HTR} = P_{GAIN} * (T_{SP} - T_{ACH}) + I_{GAIN} * \Sigma (T_{SP} - T_{ACH}) * dt + D_{GAIN} * d(T_{SP} - T_{ACH})/dt$
- Initially believed that P_{GAIN} was too high
  - Minimal impact on performance when P_{GAIN} was changed
- How can the gains be adjusted to improve stability without resorting to trial and error?



Evaluating PID Controller Behavior

- PID modeled with prevention of integral windup and constraints on the heater power
  - Long warmup or cooldown periods can result in long term error sum that takes many cycles to eliminate
  - Heater had min of 0.0 and max of 0.25 W
- Control Temp output at each timestep
- Based on the Error and the Error Sum, the contributions from the P_{GAIN} and I_{GAIN} were calculated individually
  - These values were plotted over a time when the heater was active to identify which component was the driver (Top Right)
  - The I_{GAIN} clearly is shown to be the larger contributor
- Adjusting the I_{GAIN} resulted in the much better control (Bottom Right)





Impact of Parallel Runs on Model Runtime

- Laptop used for runs: Intel® i7-3720QM with the CPU running at 2.6 GHz
  - 4 Cores, 4 Virtual Cores with Hyper Threading
  - 32 GB of RAM – no need for Virtual Memory
- SINDA/FLUINT v5.7, Patch 9
- Compare Field of Regard and Slew run times
  - 1, 2, 4, and 8 jobs submitted in parallel
  - Time(8 jobs serially) = 8 x Time(1 Job Serially)
- Exact same model so results are identical
- Running 8 jobs in parallel requires about twice as much time to get *any one* set of results
- Running 8 jobs serially takes about 4 times longer than 8 jobs in parallel to get all results
- 4 Jobs in Parallel is a "sweet spot" for getting *some* results earlier without waiting too long for *all* results

	Jobs running in Parallel			
	1	2	4	8
	Time to Run Single Job (hr)			
FOR	9.42	9.82	12.12	19.47
Slew	17.32	17.85	20.48	31.85
	Time to Run 8 Jobs (hr)			
FOR	75.33	39.27	24.23	19.47
Slew	138.53	71.40	40.97	31.85
	Performance Degradation for Single Job			
FOR	0%	4%	29%	107%
Slew	0%	3%	18%	84%
	Performance Degradation 8 Jobs			
FOR	287%	102%	24%	0%
Slew	335%	124%	29%	0%

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Impact of Fluid Modeling on Model Runtime

- Fluid modeling coupled with a thermal model adds complexity due to differences in allowable timesteps based on the scales of the thermal domain and fluid domains
- Time dependence effects on the Fluid Lumps and Paths impacts run time (Junctions and STubes are time independent, Tanks and Tubes are time dependent)
- Accuracy impact for this model is considered negligible
- Surprisingly, Junctions (Time Independent) and Tubes (Time Dependent) resulted in fastest run times.
  - Hypothesize that Tubes allow slightly larger timesteps and may have reduced backup tries when convergence criteria not met

Case	Run Time (hr)	Perf. Deg. (%)	No. TS	No. Iter	Observatory			WFI		
					Min Err (K)	Avg Err (K)	Max Err (K)	Min Err (K)	Avg Err (K)	Max Err (K)
Junctions STubes	10.92	0%	2535	25416	--	--	--	--	--	--
Junctions Tubes	**7.70**	**-29%**	**2242**	**21223**	**-0.486**	**0.002115**	**0.342**	**-0.197**	**0.004625**	**0.091**
Tanks STubes	24.02	120%	10102	56031	-0.190	0.001614	1.057	-0.174	0.004452	0.077
Tanks Tubes	31.63	190%	14297	70866	-0.450	0.002363	0.990	-0.174	0.004663	0.077

Impact of Radiation Coupling Filtering on Model Runtime

- The overall model runtime is directly influenced by the size of the solution matrix
- Density of the solution matrix strongly related to the number of radiation couplings
  - Radiation coupling filtering can substantially reduce the density of the matrix, but this filtering is generally based only on the interchange factor and not the heat exchange
- Time to fire more rays can also impact overall run time
  - Many thermal cases might use one set of radiation results
  - MCRT is inherently parallelizable
- Regardless of Number of Rays fired, number of output radks is nearly the same
  - Not worth the time to fire more rays and then throw away most of the small radks

Maximum Rays	Error (%)	Cutoff	Sum	Calc Time (min)	Output Time (min)	Total Time (min)	No Radks Output	No Radks Eliminated
10000	0	0.001	0.9	14.26	6.55	20.81	6,330,895	16,595,983
10000	1	0.001	0.9	14.25	6.4	20.65	6,332,632	16,601,196
50000	0	0.001	0.9	59.93	6.07	66	6,257,883	31,678,395
50000	1	0.001	0.9	60.6	6	66.6	6,262,274	31,671,957
500000	0	0.001	0.9	608.4	9	617.4	6,137,361	58,539,273
500000	1	0.001	0.9	575.4	7.8	583.2	6,140,926	58,396,535

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Impact of Radiation Coupling Filtering on Model Runtime

- Filtering used to output more or fewer radiation couplings from the solution database
- Filtering is performed by sorting all Bij terms from high to low and including all terms above Cutoff
- Including a Sum term will add in additional Bij terms until the Sum criteria is met
- Again, regardless of the number of rays fired, the total number of radks output is about the same for all other parameters being equal

Rays	Error	Cutoff	Sum	No Kept	No Eliminated	No Total	% Kept
10000	0	0.001	0.95	10,142,081	12,760,169	22,902,250	44%
10000	1	0.001	0.95	10,152,226	12,757,101	22,909,327	44%
50000	0	0.001	0.95	10,290,886	27,622,053	37,912,939	27%
50000	1	0.001	0.95	10,285,600	27,625,250	37,910,850	27%
500000	0	0.001	0.95	9,705,460	54,951,103	64,656,563	15%
500000	1	0.001	0.95	9,702,782	54,814,741	64,517,523	15%
10000	0	0.001	0.9	6,330,895	16,595,983	22,926,878	28%
10000	1	0.001	0.9	6,332,632	16,601,196	22,933,828	28%
50000	0	0.001	0.9	6,257,883	31,678,395	37,936,278	16%
50000	1	0.001	0.9	6,262,274	31,671,957	37,934,231	17%
500000	0	0.001	0.9	6,137,361	58,539,273	64,676,634	9%
500000	1	0.001	0.9	6,140,926	58,396,535	64,537,461	10%
10000	0	0.001	N/A	2,748,845	20,199,716	22,948,561	12%
10000	1	0.001	N/A	2,748,614	20,207,021	22,955,635	12%
50000	0	0.001	N/A	2,681,166	35,273,939	37,955,105	7%
50000	1	0.001	N/A	2,680,655	35,272,338	37,952,993	7%
500000	0	0.001	N/A	2,668,267	62,025,499	64,693,766	4%
500000	1	0.001	N/A	2,668,210	61,886,396	64,554,606	4%

Impact of Radiation Coupling Filtering on Model Runtime

- WFI Instrument includes a cryocooler, which provides some key metrics for comparing predicts
- Three runs compared:
  - Cutoff = 0.001, No Sum, 2.7 M Radks, 5.8 hrs
  - Cutoff = 0.001, 0.90 Sum, 6.3 M Radks, 12.7 hrs
  - Cutoff = 0.001, 0.95 Sum, 10.1 M Radks, 20.7 hrs
- Model with 0.95 Sum took nearly 3.5x longer than No Sum, but accuracy is questionable…
- With 0.95 sum, load on CC nearly 40% higher!!
  - This does not make sense…
- Impact is felt on 270 K Radiator, which is rejecting Cryocooler Compressor power
- IFU Detector is also greatly influenced
- Grism and Filters are also influenced, but effect should be small on these components
- Further investigation needed…

Radk Cutoff	0.001	0.001	0.001
Radk Sum	N/A	0.9	0.95
Run Time (hrs)	5.78	12.7	20.73
Cryocooler Performance			
CC Load (W)	6.712	8.035	9.442
CC Power (W)	94.5	112.0	145.2
Radiator Temp (K)	234.8	248.8	271.5
WFI Region	Avg Err (K)	Avg Err (K)	Avg Err (K)
WFI_170K_RAD	--	0.05	0.08
WFI_270K_RAD	--	14.19	22.88
WFI_CC_ELEX	--	3.44	5.03
WFI_EW_FILTERS	--	0.06	-1.26
WFI_EW_GRISM	--	-1.84	-3.64
WFI_FPA_COVER	--	1.29	2.45
WFI_FPA_MOSAIC	--	1.21	2.28
WFI_IFU_DET	--	7.94	19.39
WFI_OB	--	-0.06	-0.14

Why is CC Load so different? Can 5-10% more FOV really cause this?

Impact of Radiation Coupling Filtering on Model Runtime

IFU Detector		0.001 Cutoff, 0.95 Sum			0.001 Cutoff, 0.90 Sum			0.001 Cutoff		
Temp/Source:		118.5		0	110.55		0	99.112		0
Lin Heat In:				1.576			1.614			1.647
Lin Heat Out:				-2.667			-2.321			-1.938
Rad Heat In:				1.081			0.7096			0.2853
Rad Heat Out:				0			0			0
Node	Type	Temp j	Cond j	Heat j	Temp j	Cond j	Heat j	Temp j	Cond j	Heat j
IFU HX	L	92.73	21.395	-2.667	92.589	21.395	-2.321	92.419	21.395	-1.938
IFU Bench	L	165.55	2.52	1.576	165.75	2.52	1.614	165.87	2.52	1.647
IFU Focus Mechanism	R	163.25	5.15E-07	1.80E-05	164.6	5.15E-07	1.88E-05	165.94	5.15E-07	1.96E-05
IFU ASIC	R	164.78	1.71E-05	0.0001	165.03	1.71E-05	0.0001	165.15	1.71E-05	0.0001
IFU Mounts	R	165.99	0.0001	0.0008	166.18	0.0001	0.0008	166.3	0.0001	0.0008
IFU Optics	R	164.41	0.0009	0.0314	164.94	0.0009	0.0322	165.39	0.0009	0.0328
EW Filters	**R**	**166.75**	**0.0024**	**0.0657**	**166.69**	**0.0137**	**0.4286**	**0**	**0**	**0**
IFU Bench	R	165.55	0.003	0.0718	165.75	0.003	0.073	165.87	0.003	0.0741
IFU Enclosure	R	166.06	0.0057	0.1724	166.24	0.0057	0.175	166.37	0.0057	0.1775
EW Grism	**R**	**164.63**	**0.0288**	**0.739**	**0**	**0**	**0**	**0**	**0**	**0**

- Grism and Filters should not even be able to “see” the IFU Detector…
- Why does adding in more couplings drastically change the heat flow to Grism and Filters?
- Same effect seen for IR MOSAIC plate…software vendor contacted

Impact of Radiation Coupling Filtering on Model Runtime

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- Software vendor found an error in the Summation routine related to the model size and addressable memory
- Quickly fixed and results regenerated
- Errors were much more acceptable
- Run time with 0.95 Sum was about 50% more than 0.90 Sum and 300% more than No Sum
- Errors were generally within 1 K
- Hybrid approach developed which extracted Radks from 95% sum case for cryo components and No Sum case for non-Cryo components
  - This results in better prediction of the Cryocooler load while still improving run time over 0.90 Sum case

Radk Cutoff	0.001	0.001	0.001	0.001
Radk Sum	N/A	0.9	0.95	N/A::0.95
Run Time (hrs)	5.87	12.32	18.18	10.38
Cryocooler Performance				
CC Load (W)	6.72	6.91	7.10	7.09
CC Power (W)	94.59	96.05	97.29	97.17
Radiator Temp (K)	234.8	236.1	237.3	237.2
WFI Region	Avg Err (K)	Avg Err (K)	Avg Err (K)	Avg Err (K)
WFI_170K_RAD	0.0286	0.0113	--	0.0316
WFI_270K_RAD	0.8293	0.2939	--	-0.6533
WFI_CC_ELEX	-2.0273	-1.2768	--	-2.3948
WFI_EW_FILTERS	0.1034	-0.0067	--	0.1689
WFI_EW_GRISM	0.0452	-0.0384	--	0.1015
WFI_FPA_COVER	0.3786	0.1736	--	0.0087
WFI_FPA_MOSAIC	0.3635	0.1634	--	0.0081
WFI_IFU_DET	0.0724	0.0724	--	0.0363
WFI_OB	-0.0490	-0.0278	--	-0.0143

- Cryocooler is sensitive to more of the Radks that are filtered than other regions
- Would be a nice feature for S/W vendors to filter based on Energy (Bij * (T^4 – T^4))

Conclusions and Moving Forward

- WFIRST is a large and complex model already, even in Phase A
  - *Complexity driven by requirements and analysis questions (STOP, tight stability)*
- As Phase A Trade studies are underway, analytical efforts are needed to judge and evaluate potential designs and to verify that requirements can be met
- The ability to quickly exercise the model is critical to providing data
  - *Simulating realistic slew profiles instead of only Field of Regard constraints*
  - *Ability to reasonably adjust and tune PID parameters to meet stability requirements*
- Effective usage of computational resources
  - *Parallel job submission should take into account if partial data is needed sooner*
  - *Fluid modeling with time dependent lumps greatly increased run time, but seemed to decrease run time for time dependent flow paths*
  - *Firing more rays and filtering the small terms wastes computing time*
  - *Including more (smaller) radks increases run time, but accuracy may be necessary for cryo regions*
    - *Filter Radks based on Energy from previous runs results instead of just geometric factors*
- No substitute for careful evaluation of model predicts (models must still follow physics!)
  - *Bug found in code that gave questionable results. Correction resulted in more realistic predicts*
  - *The software will not tell you when it is wrong and cannot replace analyst's judgment and experience*
- WFIRST now in Phase A and proceeding to SRR…more to come next year!