A parametric model of the CELT

Steve Padin & Doug MacMartin

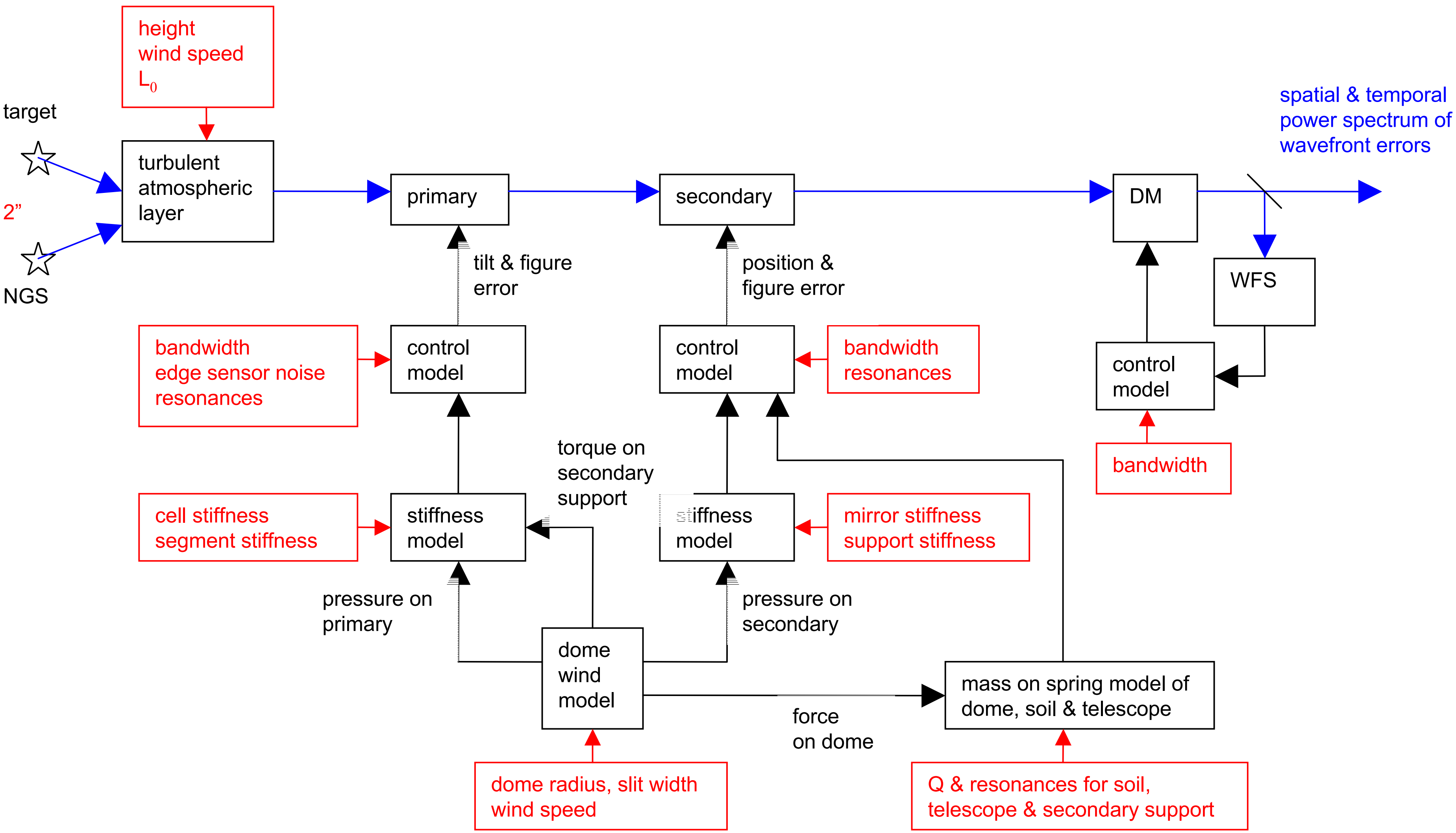
California Institute of Technology

Goal is a top-level model of the telescope & enclosure

captures trends in performance, cost & risk
simple, analytical & numerical models
fairly wide view of the design space, but with limited fidelity
helps select a point design for more detailed analysis

Current focus of telescope design at Caltech is on dynamics, particularly wind (complements the work done in the CELT conceptual design).

CELT wind & atmosphere model



Modeling wind, stiffness & control

A Zernike mode decomposition is appropriate for modeling:

1. Optical aberrations
2. Pressure fluctuations on circular structures e.g. mirrors
3. Phase fluctuations in the atmosphere

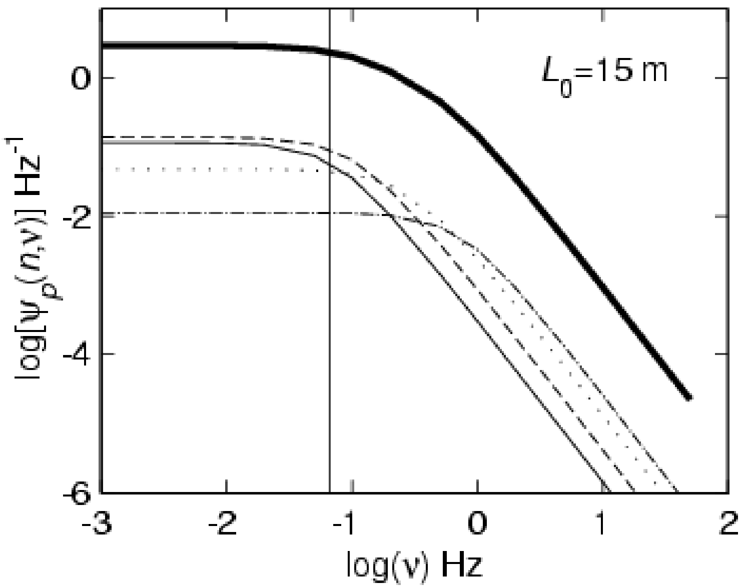
Not well-matched to a mechanical description of the telescope.

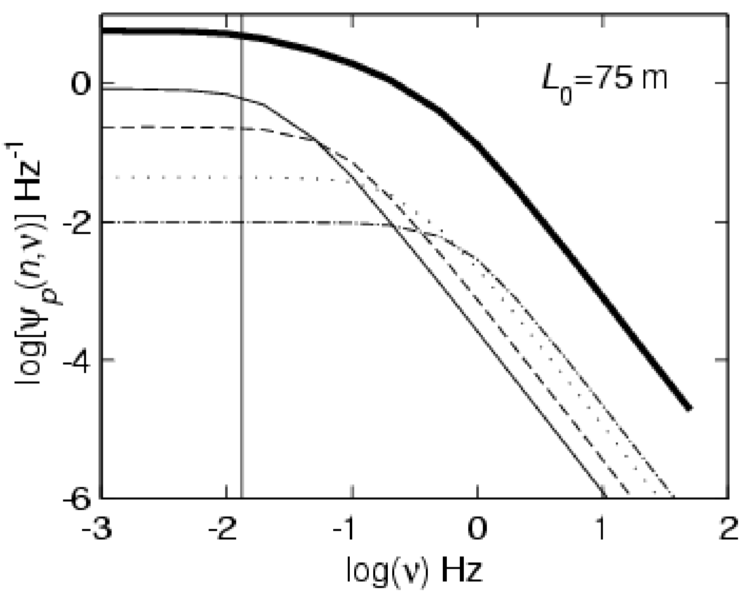
A structural mode decomposition is more appropriate for modeling stiffness & control.
Not easy to include in a parametric model.

Simple wind buffeting model: (currently ~80 telescope + ~20 cost parameters)

1. Zernike decomposition of a frozen, turbulent pressure field
2. Assign stiffness based on mode feature size (not trivial for a Zernike expansion)
3. Radial degree is mode index
4. Model control as a high-pass filter for disturbance & a low-pass filter for noise

<u>Normalized spatial & temporal power spectra of pressure fluctuations</u>





Bold	temporal power spectrum
Solid	*n*=1
Dash	*n*=5
Dotted	*n*=20
Dash-dot	*n*=60

Vertical lines at outer-scale wind crossing frequency

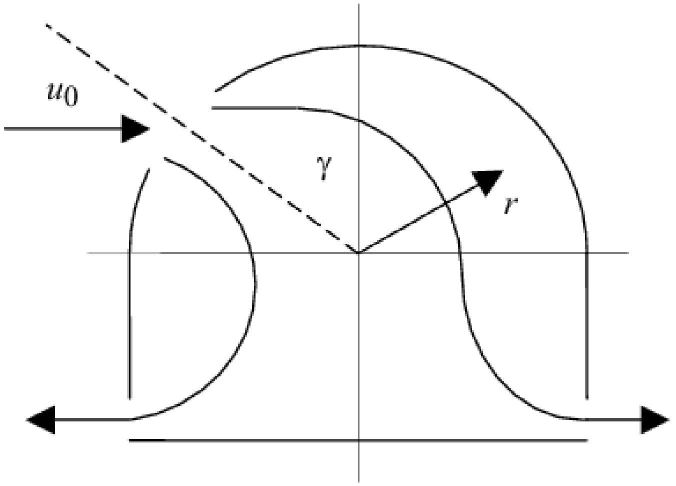
Spectra roll off as $\nu^{-7/3}$ at high frequency

Enclosure model - important because enclosure cost is a strong function of its size

Wind speed outside the enclosure sets the scale for the pressure field.

Assumptions:

1. $u_{rms}(r)$; r for an enclosure with no wall vents (Keck wind-tunnel measurements)
2. Conservation of power between air entering the slit & air flowing across a section through the center of the dome



$$u_{rms}(r)=u_0(r/R_d)(R_h/R_d)^{2/3}[(5/2)\sin\gamma]^{1/3}$$

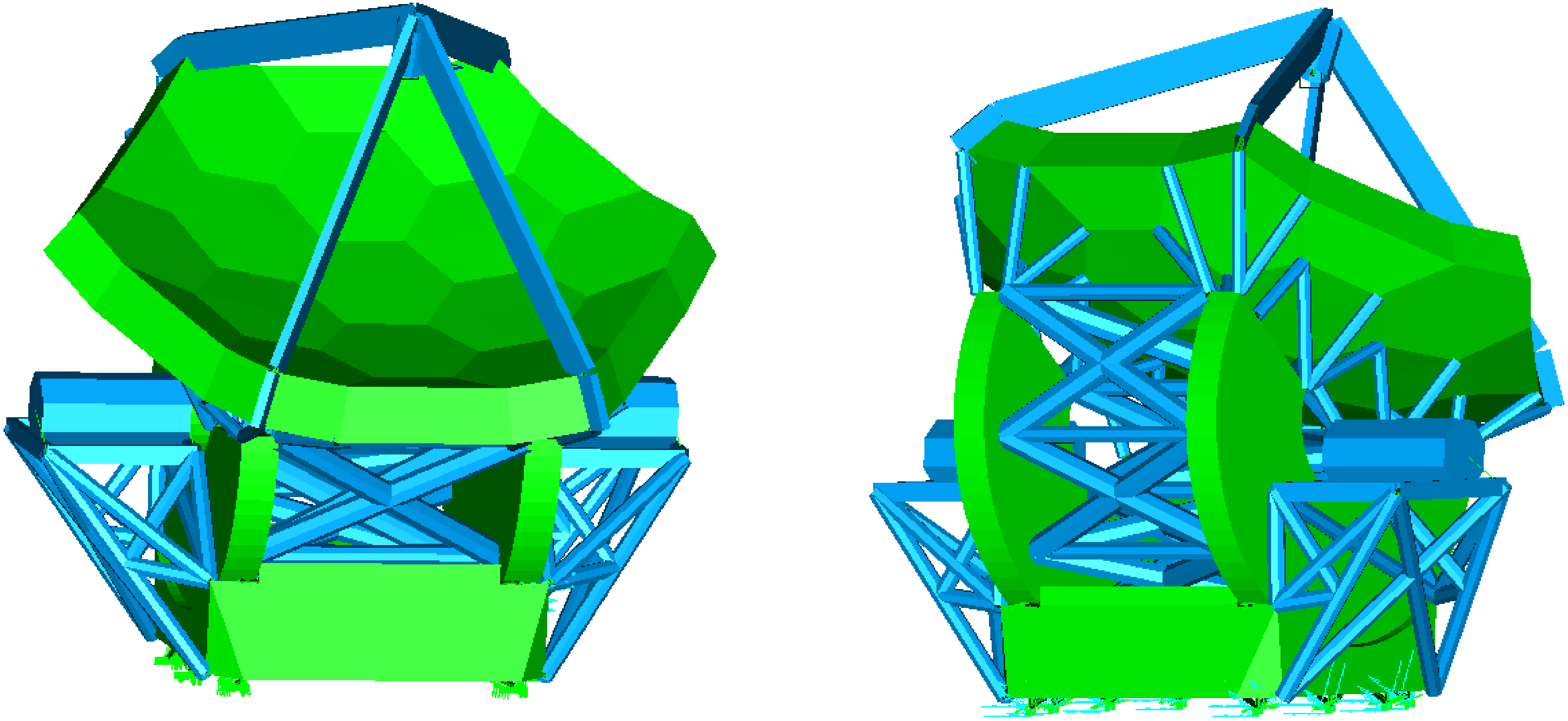
R_d = dome radius, R_h = slit radius

Observations based on measurements at Gemini south:

1. At the primary, all the wind power is in the turbulence
   mean $\langle u_p \rangle \sim 0$, standard deviation $\sigma_p \sim u_{rms}(R_p/2)$
2. At the secondary, about half the wind power is in the mean flow
   $\langle u_s \rangle \sim \sigma_s$, $\sigma_s \sim (1/2)^{1/2} u_{rms}(d_{es})$,
   d_{es} = distance from el axis to secondary

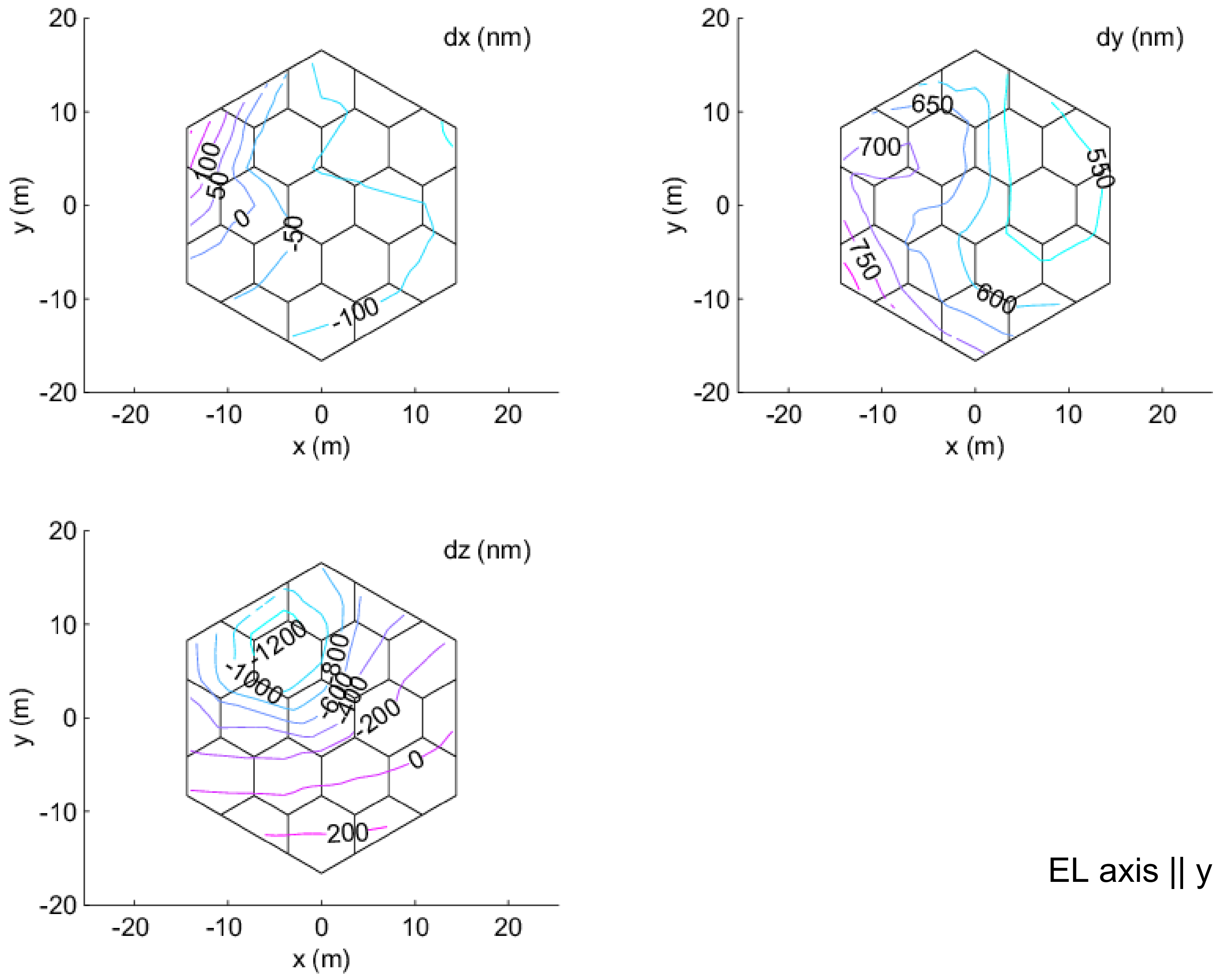
Caltech (MacMartin, Padin) & AURA (Angeli, Vogiatzis)

UA 30m f/0.5 telescope



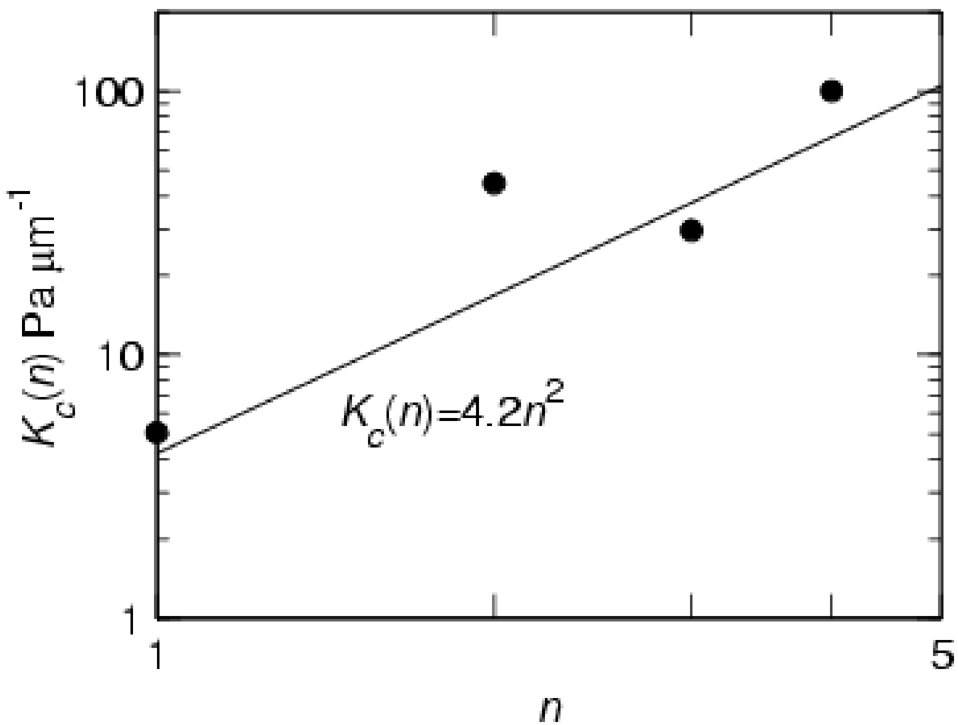
Caltech (Padin) & University of Arizona (Davison)

Primary deformations for 100 Pa applied to the segment at (-3.6, 6.2) in the UA 30m telescope



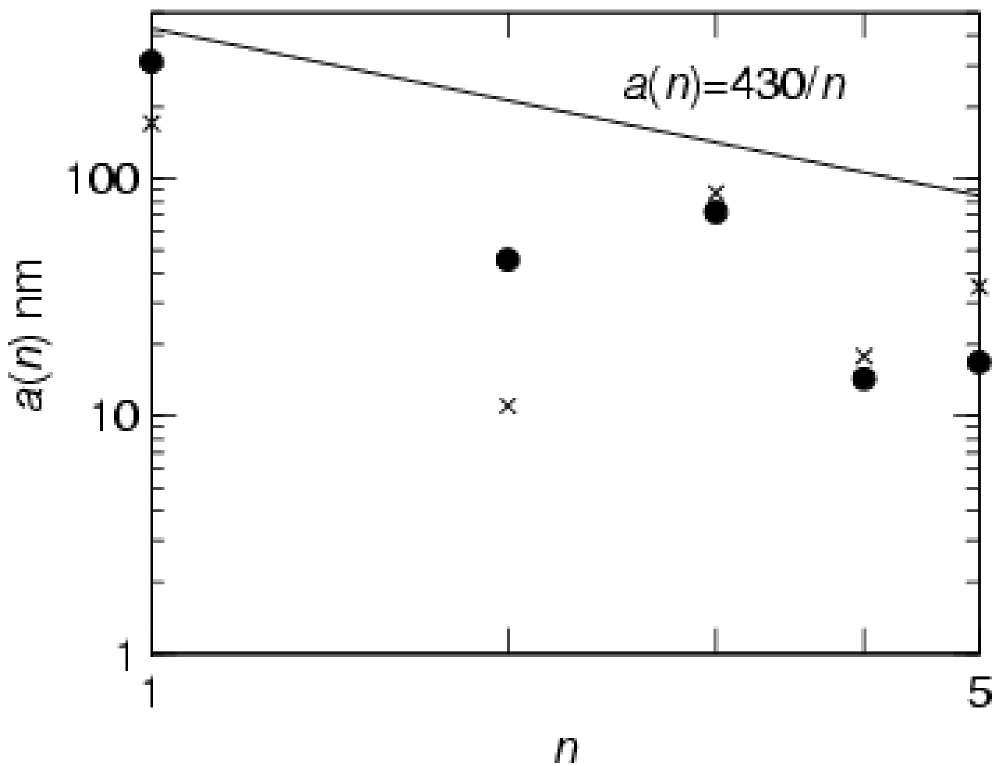
EL axis || y

<u>Primary mirror cell stiffness for the UA 30m telescope</u>



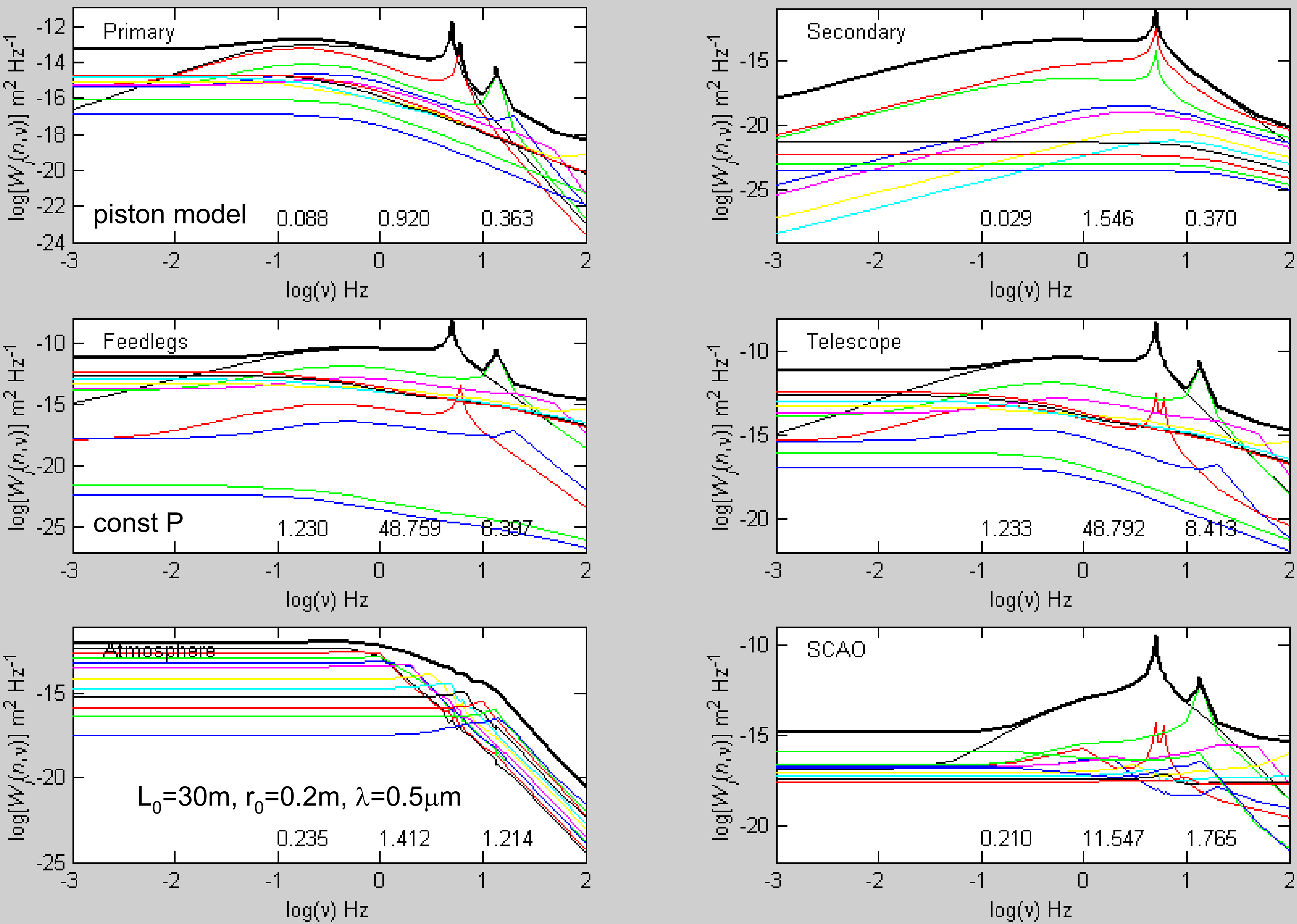
line – simple model with $K_c(n)$; n^2, axial (n=2) gravitational deflection from FEA model
solid circles – FEA results (Zernike mode pressure distribution applied to primary)

Primary deformation Zernike coefficients for 1 kN applied to the secondary of the UA 30m



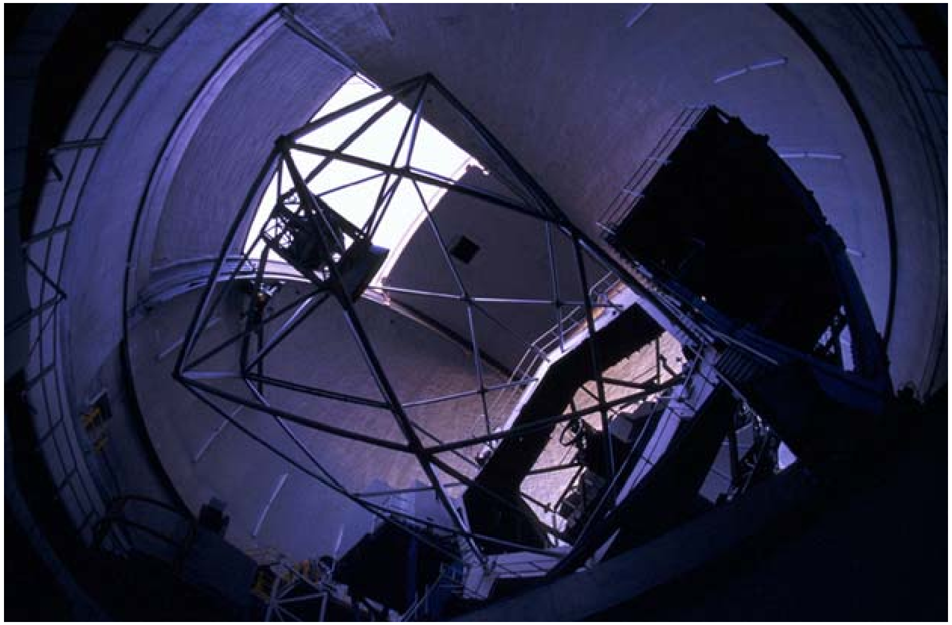
line – simple model with $a(n\text{=odd})=2nt/\pi R_p^3 K_c(n)$ (t=applied torque)
solid circles & crosses – FEA results for 2 orthogonal directions of the applied force

CELT wavefront error model *n*=[1,2,3,4,5, 9 13 19 29 39 49], bold lines – temporal power spectra

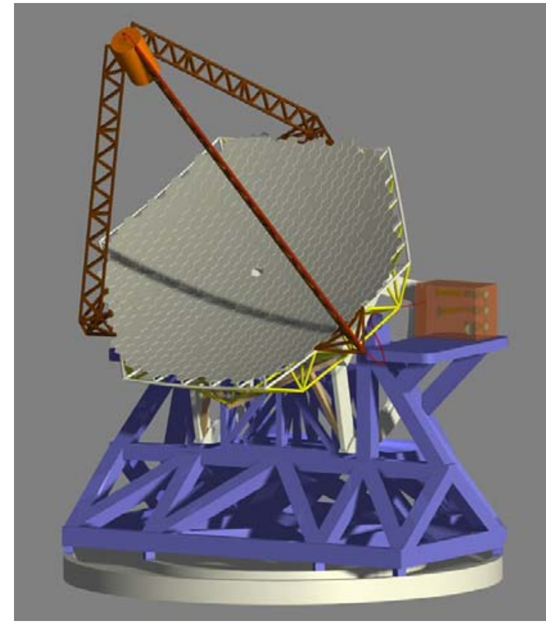


numbers - image diameter (arcsec), rms wavefront error (μm), rms wavefront error for *n* >1 (μm)

Keck

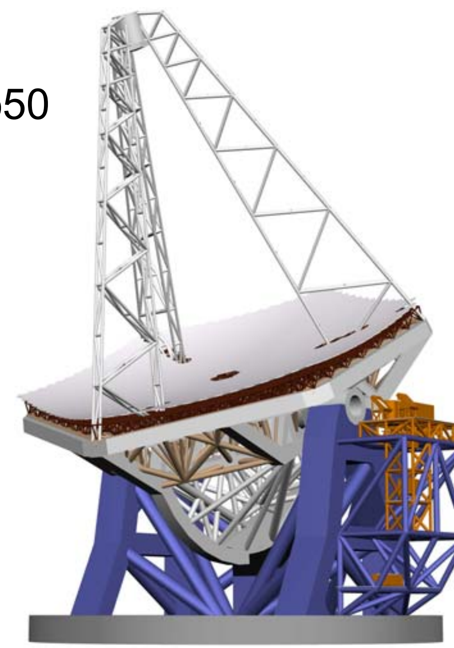


GSMT



Palomar

Euro50



Reducing the effects of wind buffeting on the feedlegs

(an example of design trade-offs with a parametric model)

1. Point away from the wind
   Requires dynamic scheduling

2. Increase mirror cell stiffness
   Probably increases cell mass – might push el axis behind primary
   Reduces gravitational deflections – shorter actuator stroke

3. Reduce primary focal ratio
   Increases polishing cost - might reduce segment diameter

4. Increase dome diameter or install wind fences
   Increases cost

5. Adaptive secondary
   GSMT solution
   Efficient if an adaptive secondary is required for AO

6. Independent secondary support structure
   Force-based coupling to primary mirror cell – more difficult secondary position control
   Completely independent structure – increases mass of telescope

Cost & risk modeling

1. Cost

(i) Parametric cost models usually involve fits to cost data for many similar projects

e.g. Meinel's telescope cost;$D^{2.7}$
Cost of steel structures ~ $22/kg
An analysis of mirror polishing costs might give cost(R_{seg}, C_{20}, C_{22})

(ii) Can also include explicit cost dependencies

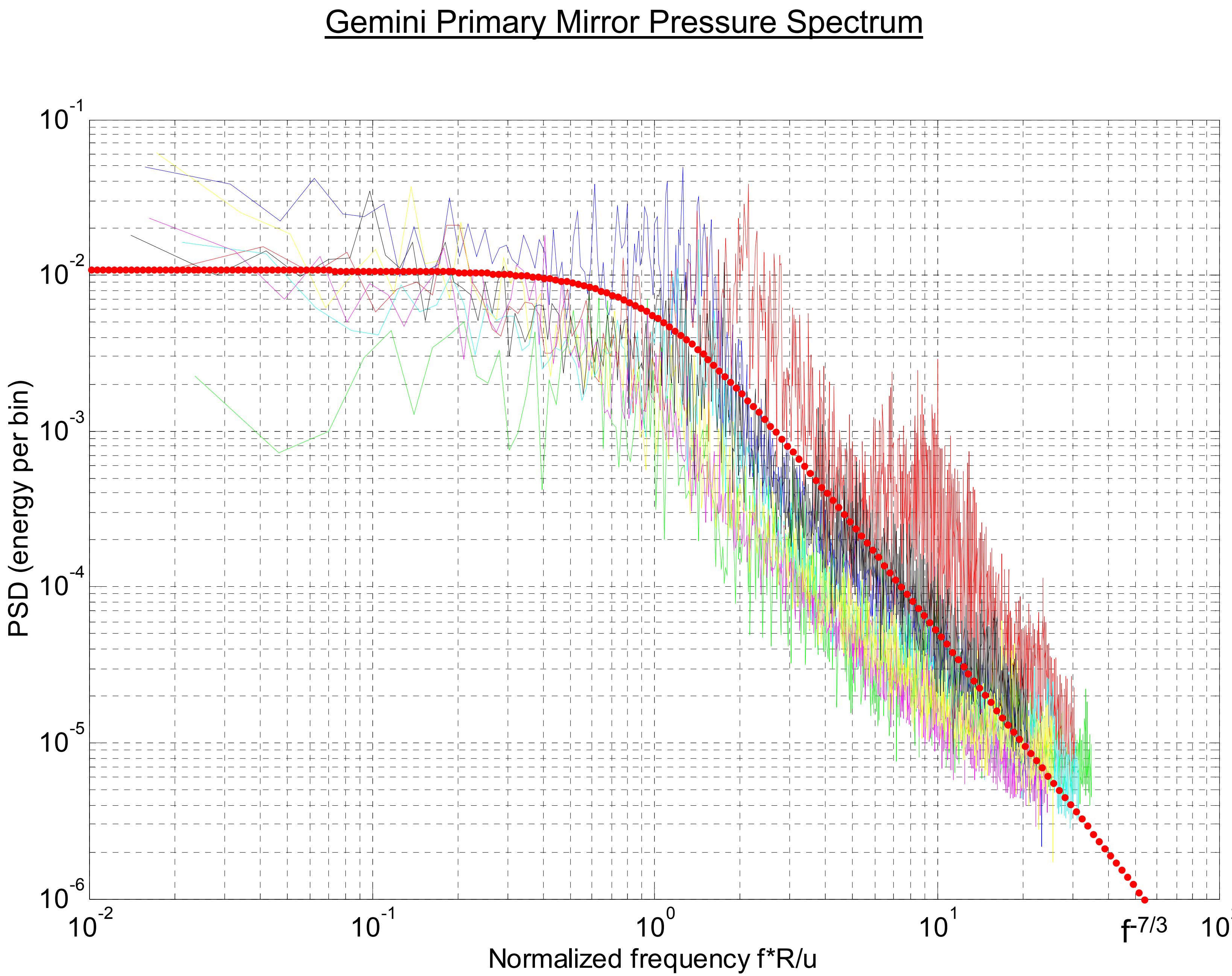
e.g. cost of actuators ; number of segments

2. Risk

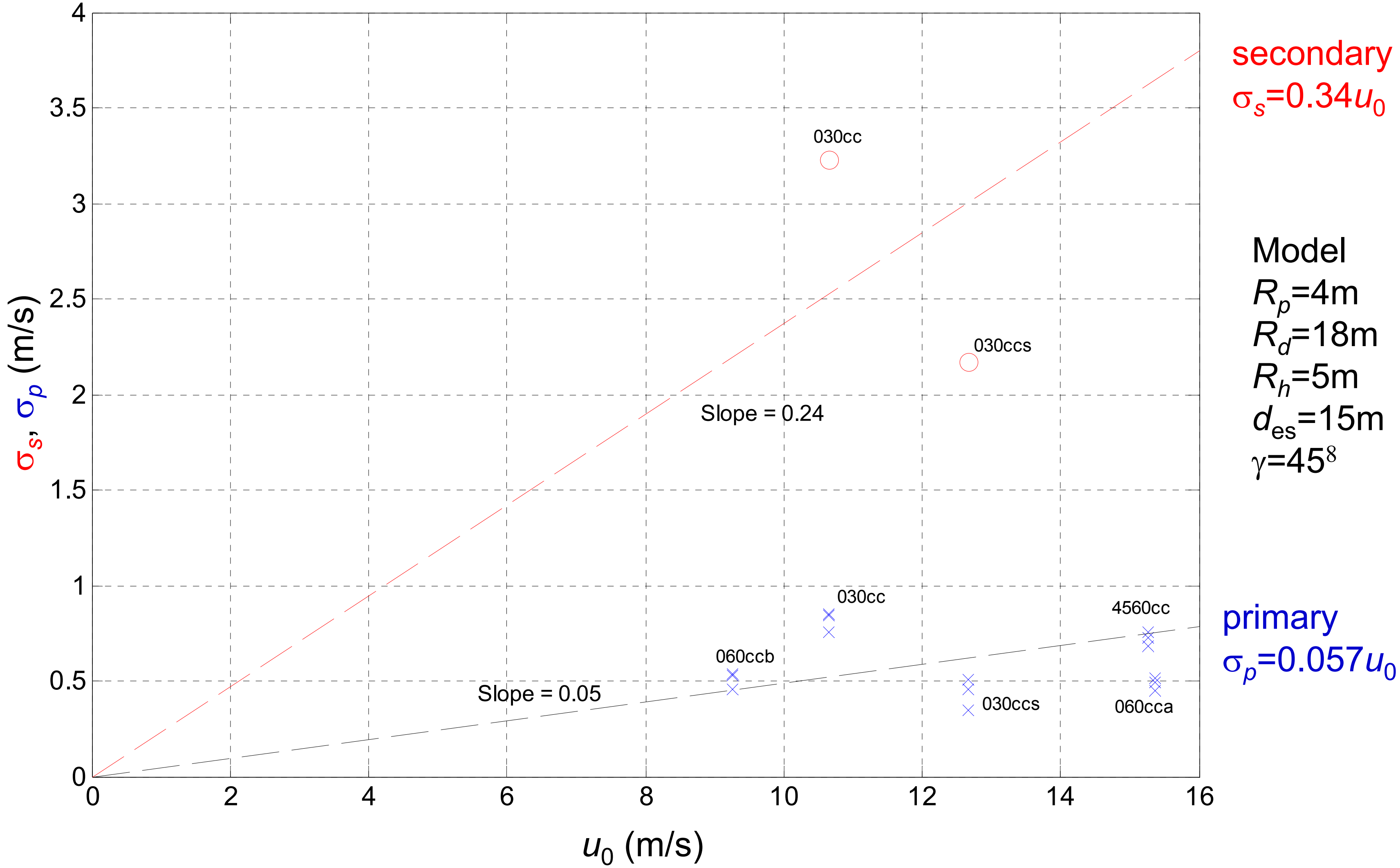
Very difficult to accurately model errors in cost and schedule
A simple approach is to include an estimate of cost error

e.g. risk=standard deviation/cost

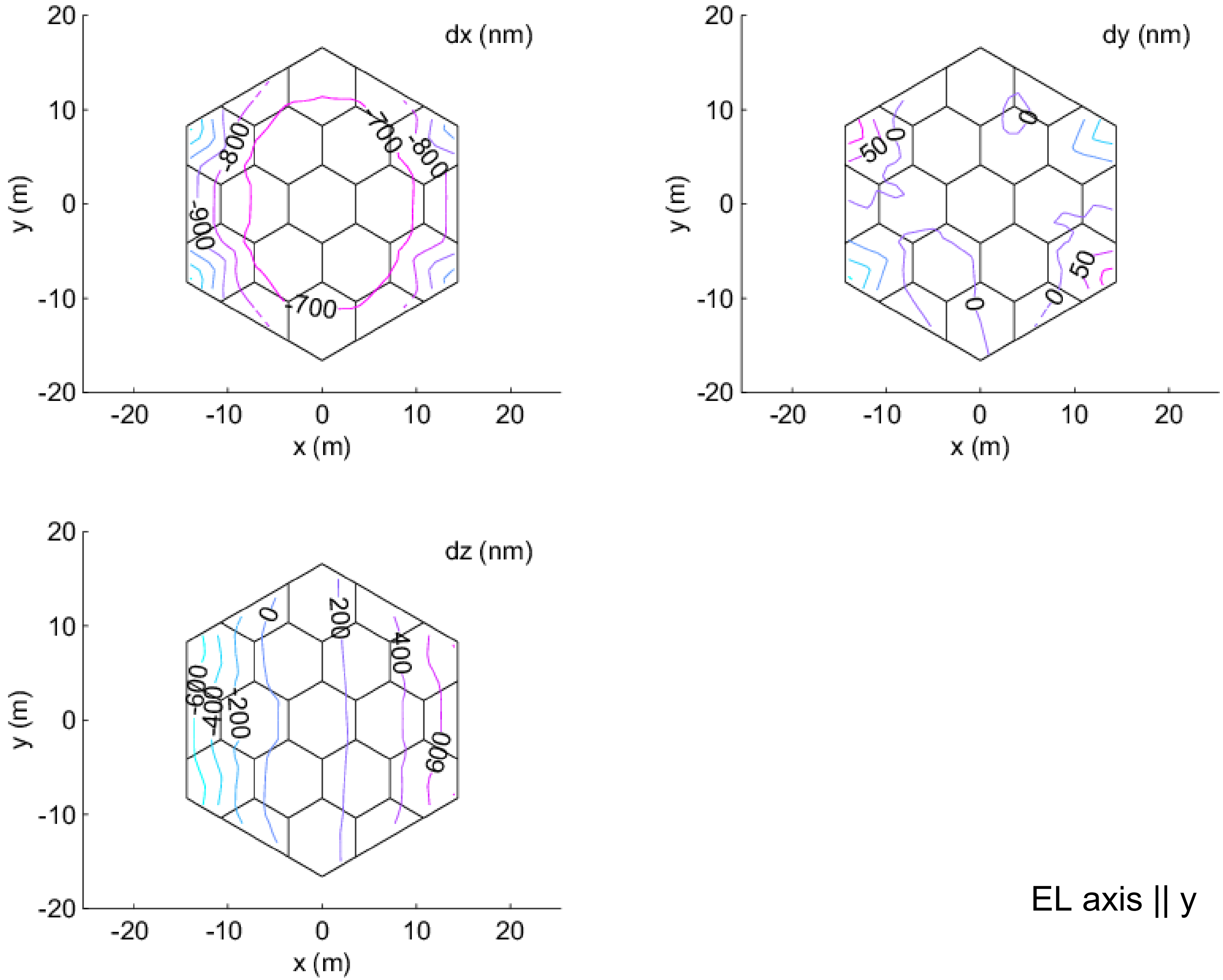
risk	
0.1	vendor quote on a standard part
0.3	similar to a previous experience, needs some development
1.0	engineer's guess


Gemini Primary Mirror Pressure Spectrum
PSD (energy per bin)
Normalized frequency f*R/u
10^-1
10^-2
10^-3
10^-4
10^-5
10^-6
10^-2
10^-1
10^0
10^1
10^2
f^-7/3

Gemini wind measurements & enclosure model predictions

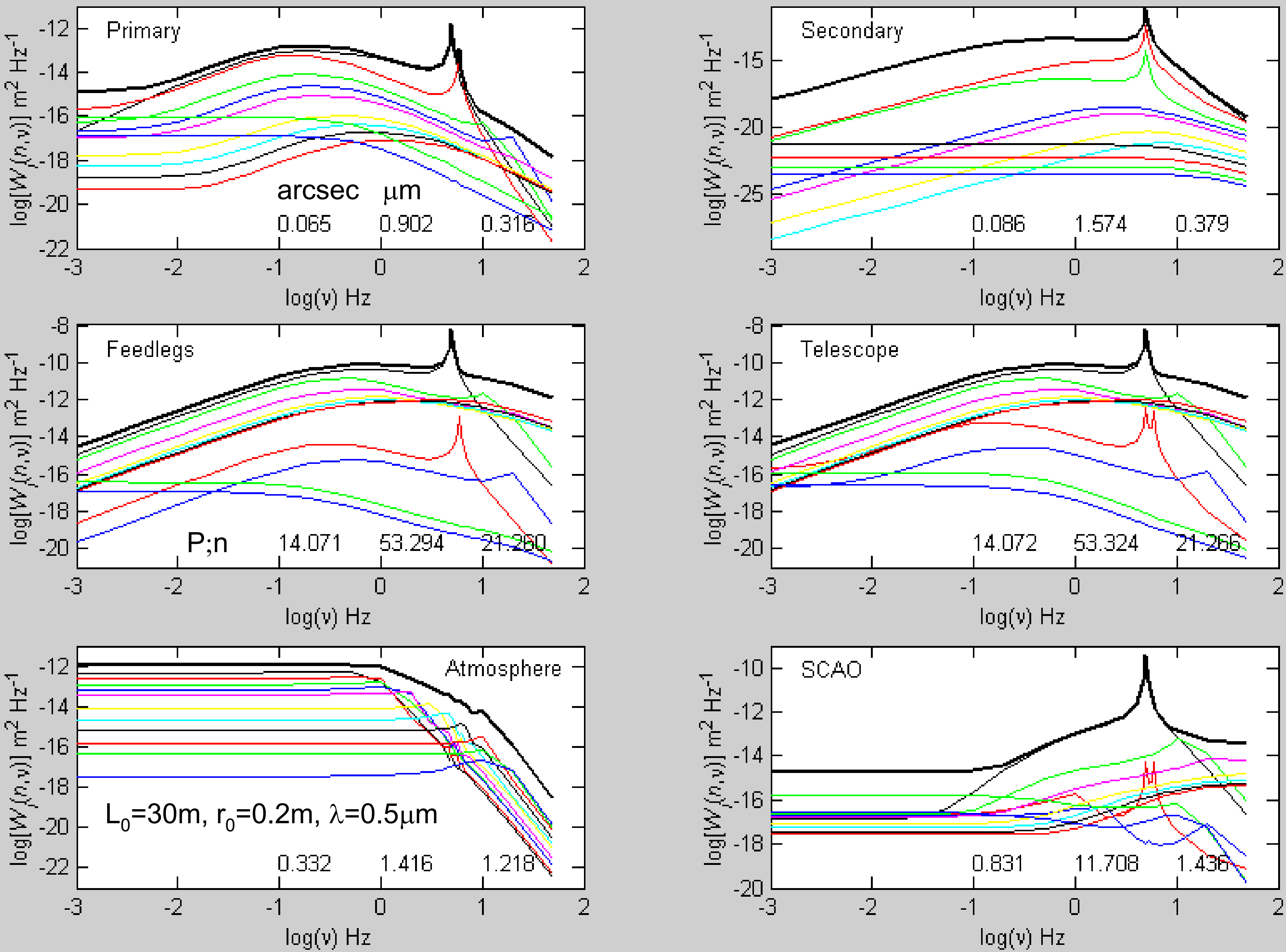


Primary deformations for 1 kN applied to the secondary of the UA 30m telescope



EL axis || y

CELT wavefront error model *n*=[1,2,3,4,5, 9 13 19 29 39 49], bold lines – temporal power spectra



numbers - image diameter (arcsec), rms wavefront error (µm), rms wavefront error for *n* >1 (µm)

Summary

We need parametric & detailed models which evolve with the project.

A top-level, end-to-end parametric model is most important.
- Maintains an overall view of the project.
- Allows design trade-offs early, when changes are cheap (cf. expensive “fixes” later).
- “What if?” questions can be answered quickly.

  Important if the constraints (e.g. max. cost) are changing.

Detailed models are required to give an accurate performance & cost for a particular point design.

~3 FTE years (~0.2% of the CELT) to build a really useful top-level model of the telescope & enclosure; 2x this to refine & check the models, modify the conceptual design & take a first cut at detailed modeling.

Modeling the CELT

Goal is an "optimized" observatory design that meets our scientific requirements.

A sound approach is to build an end-to-end model which captures trends in performance, cost & risk.

Parametric models for design optimization

Custom models
(fairly simple, mostly analytical, limited fidelity, wide field of view)

Detailed models for point design analysis

Mix of custom & commercial packages e.g. CFD, FEA, ray tracing
(detailed, accurate analysis, but difficult to change parameters)

Models must be developed iteratively throughout the project to support design, construction & commissioning.

Current focus of telescope design at Caltech is on dynamics, particularly wind.

(complements the work done in the conceptual design)

Immediate goal is a top-level parametric model of performance & cost for the telescope & enclosure.

Building a parametric model

1. Keep it simple, but capture key performance & cost parameters.

2. Test model components using measurements or other models (e.g. FEA).

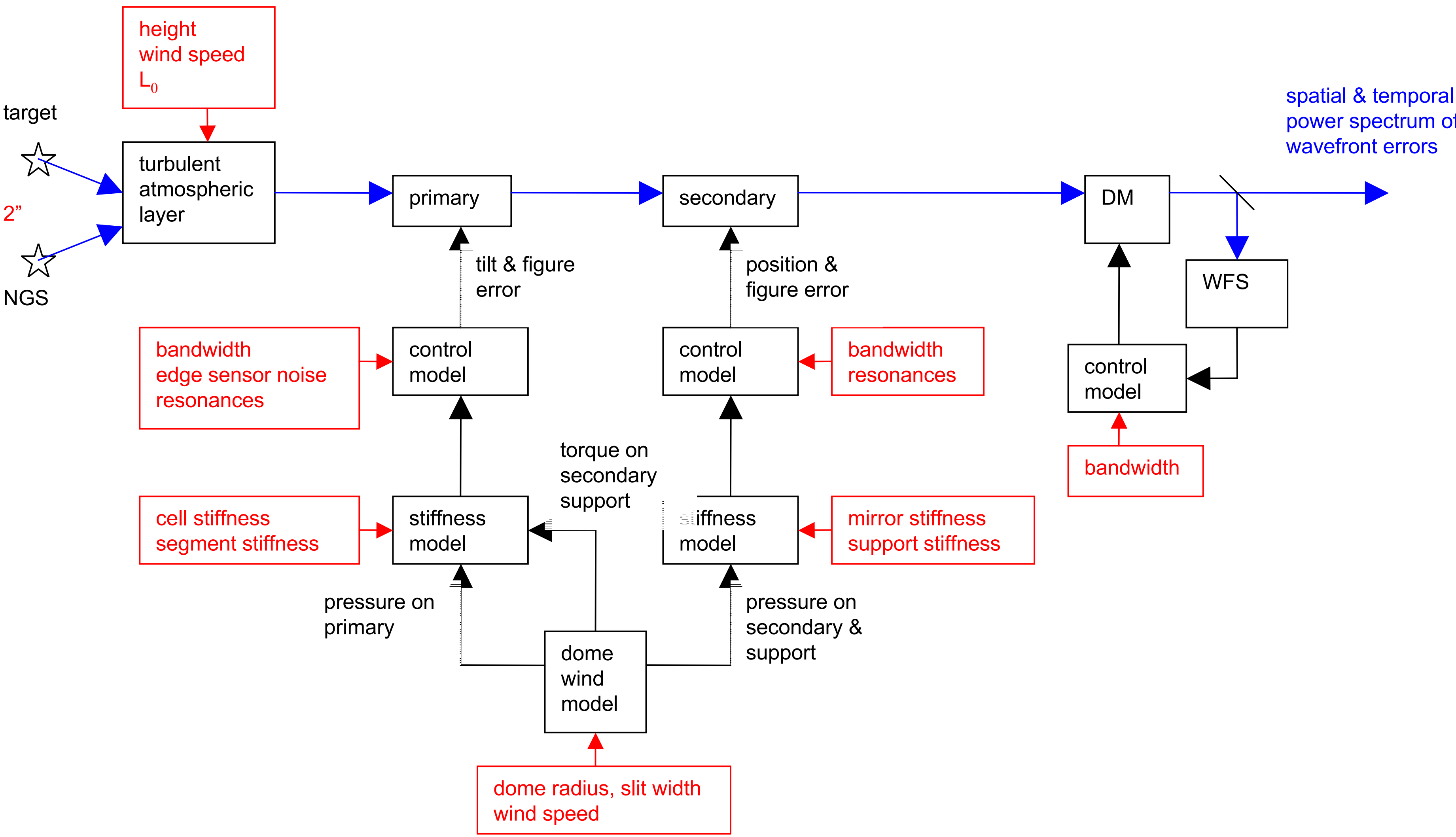
3. Focus on performance & sources of errors, to provide a check on detailed models where the emphasis tends to be on equipment.

e.g. error-based model for the dome/telescope/AO

	error	constrains
quasi-statics	aberrations, emissivity	optical design
	gravity	structure, aO
	temperature	dome, aO
dynamics	atmospheric turbulence	AO
	wind	dome, structure, aO, AO
	vibrations	structure, aO, AO

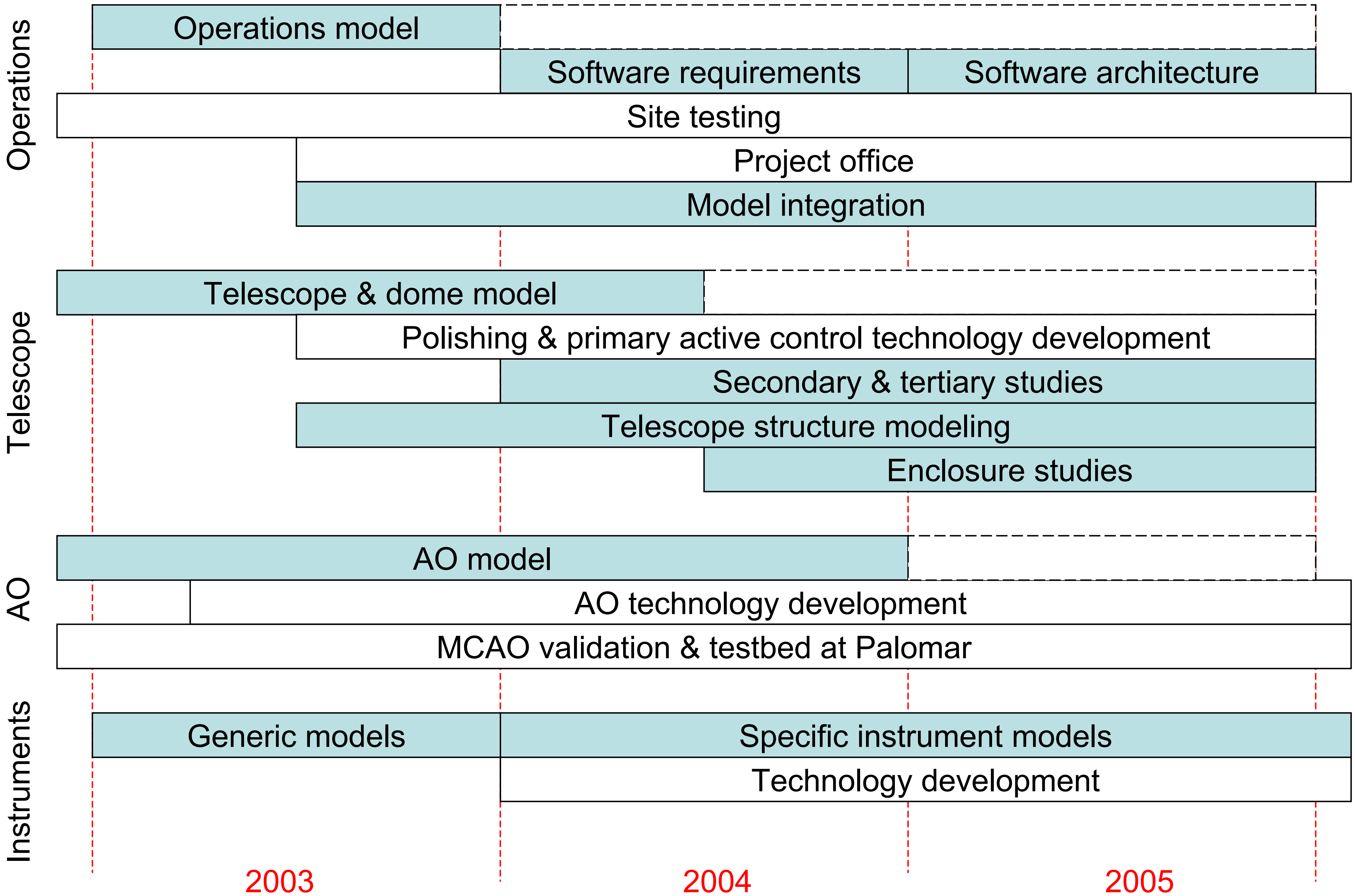
4. A rough estimate is better than nothing.
   Some things (e.g. analysis software) are difficult to model early in the project, and modeling takes time, which seems to slow down the project.
   But, if you don't model it, you might have to fix it later.

CELT wind & atmosphere model



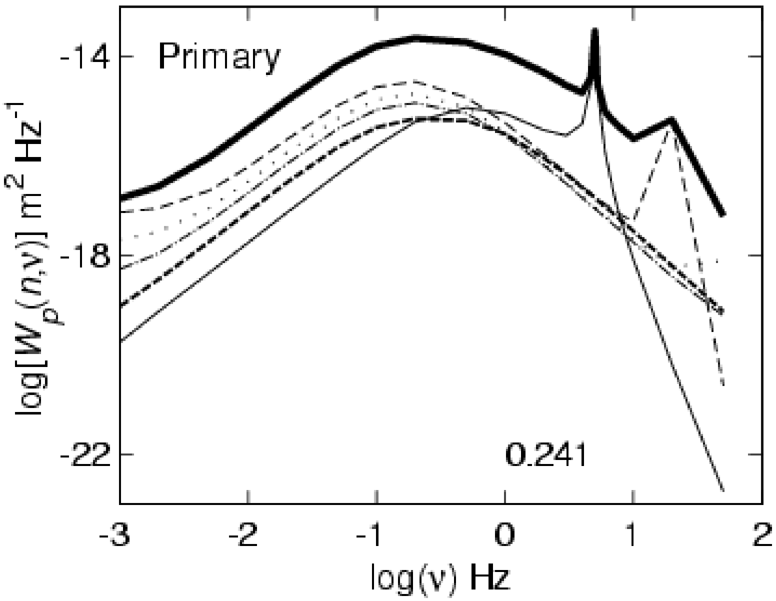
Resources for a CELT dome/telescope model

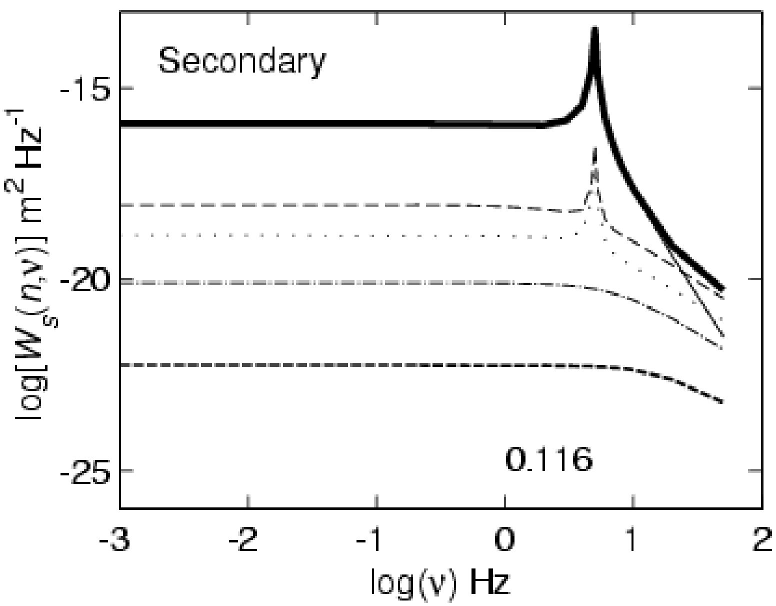
model	task	FTE weeks	
quasi-static			
aberrations	ray tracing (image size for different optical designs)	2	
emissivity	gap model (based on gravitational deflections)	2	
throughput	reflectivity model	2	
temperature	simple deformation model	2	
dynamic			
wind	CFD modeling of dome air flow	36	contract
	check wind pressure models (Gemini data?)	24	
	ray tracing (image size vs. secondary position error)	8	
	FEA to improve stiffness models	32	contract
	models of (isolated?) secondary supports	24	contract
	control models	24	
vibrations	analyze measurements from Keck	4	
	telescope mass & stiffness model	6	
	dome/soil/pier model (for wind buffeting on dome)	12	
	secondary chopping model	24	
preliminary cost			
dome	cost vs. size	8	contract
telescope structure	cost vs. f#, D etc.	24	
optics	perturbation analysis based on Phase 1	24	
	check models against existing designs	8	
detailed design to check parametric models			
modify current CELT structure		32	contract
wind & vibration FEA		24	contract
wavefront error analysis (ray tracing)		24	contract
	total	346	



Operations
Operations model
Software requirements
Software architecture
Site testing
Project office
Model integration
Telescope
Telescope & dome model
Polishing & primary active control technology development
Secondary & tertiary studies
Telescope structure modeling
Enclosure studies
AO
AO model
AO technology development
MCAO validation & testbed at Palomar
Instruments
Generic models
Specific instrument models
Technology development
2003
2004
2005

Wavefront errors due to wind buffeting for a Keck telescope

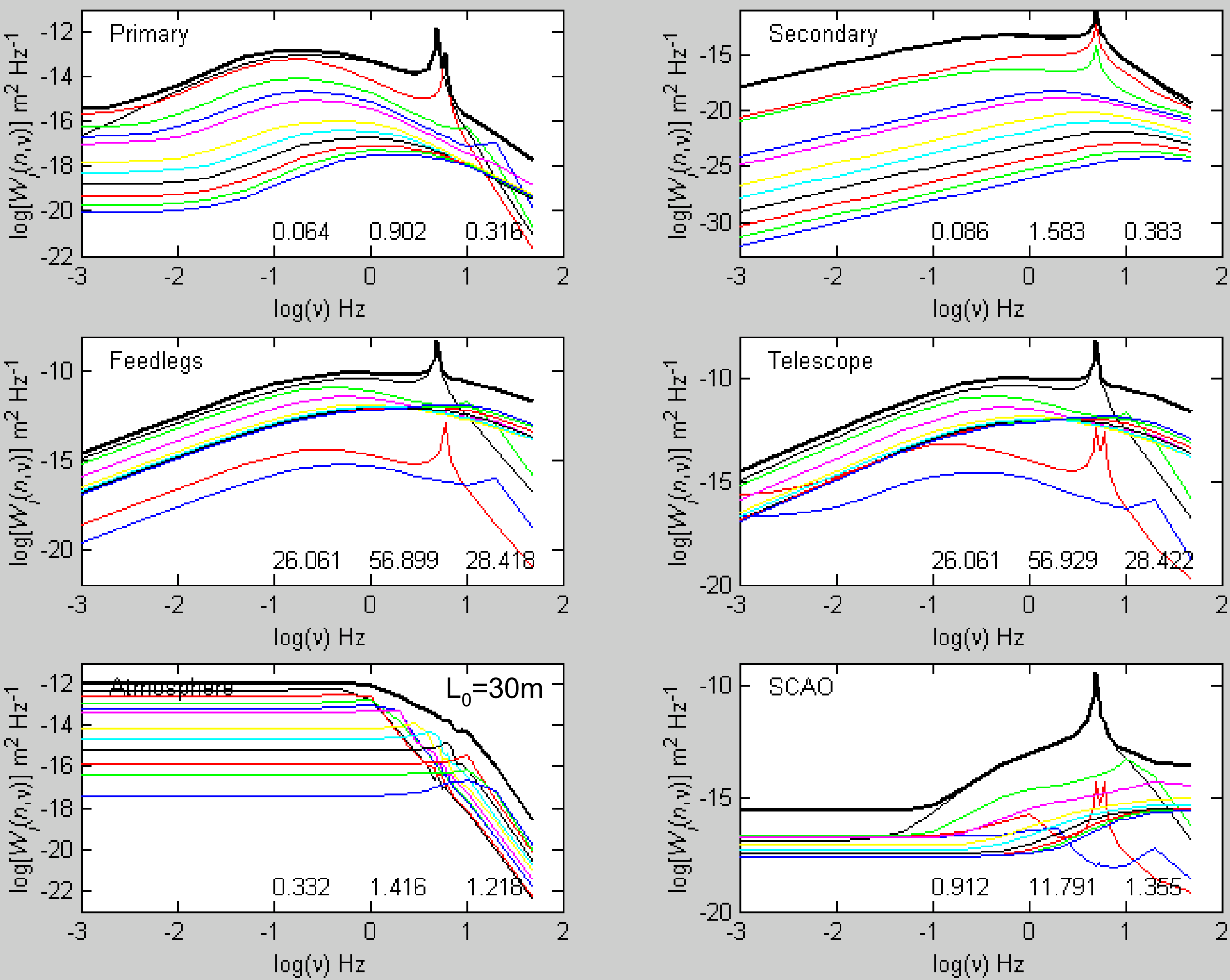




Bold	temporal power spectrum
Solid	n=1
Dash	n=2
Dotted	n=3
Dash-dot	n=5
Heavy dashed	n=13

The number in each plot is the total rms wavefront error (excluding n=0) in μm.

CELT wavefront error model *n*=[1,2,3,4,5, 9 13 19 29 39 49], bold lines – temporal power spectra



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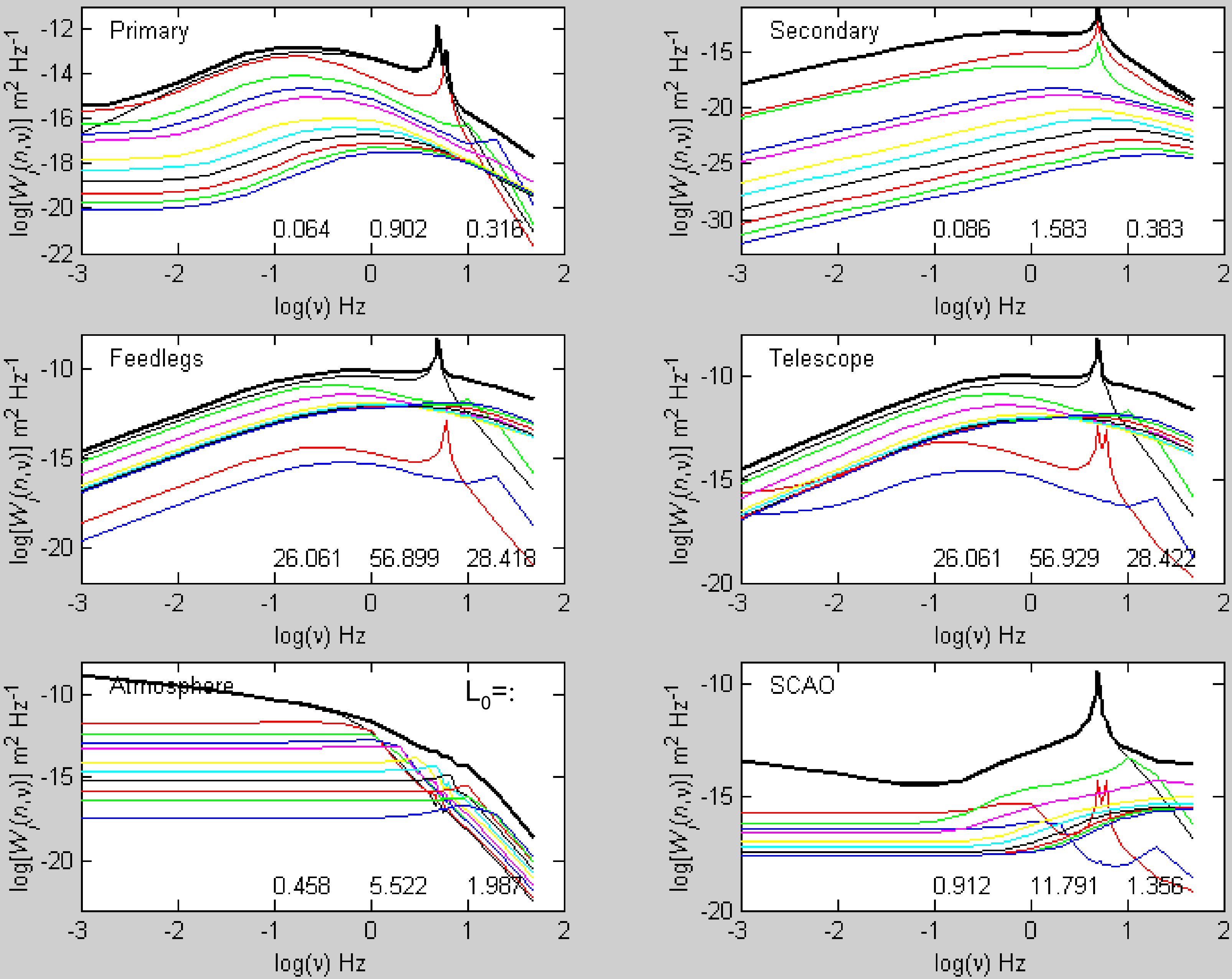
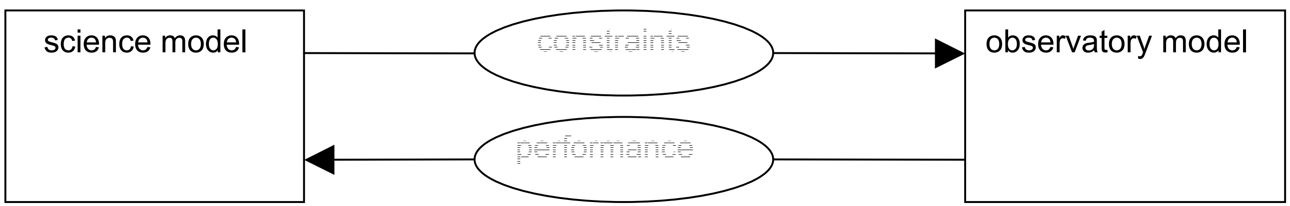


numbers - image diameter (arcsec), rms wavefront error (μm), rms wavefront error for *n* >1 (μm)

Project with a point design

<u>rough constraints model</u>
1. low fidelity
2. provides just a few constraints

<u>point design</u>
1. high fidelity (except perhaps software)
2. complex, accurate performance model
3. fairly accurate cost model
4. rough risk model



technical	organizational
PSF	cost
emissivity	risk

Project with parametric & detailed models

rough constraints model

1. low fidelity
2. provides just a few constraints

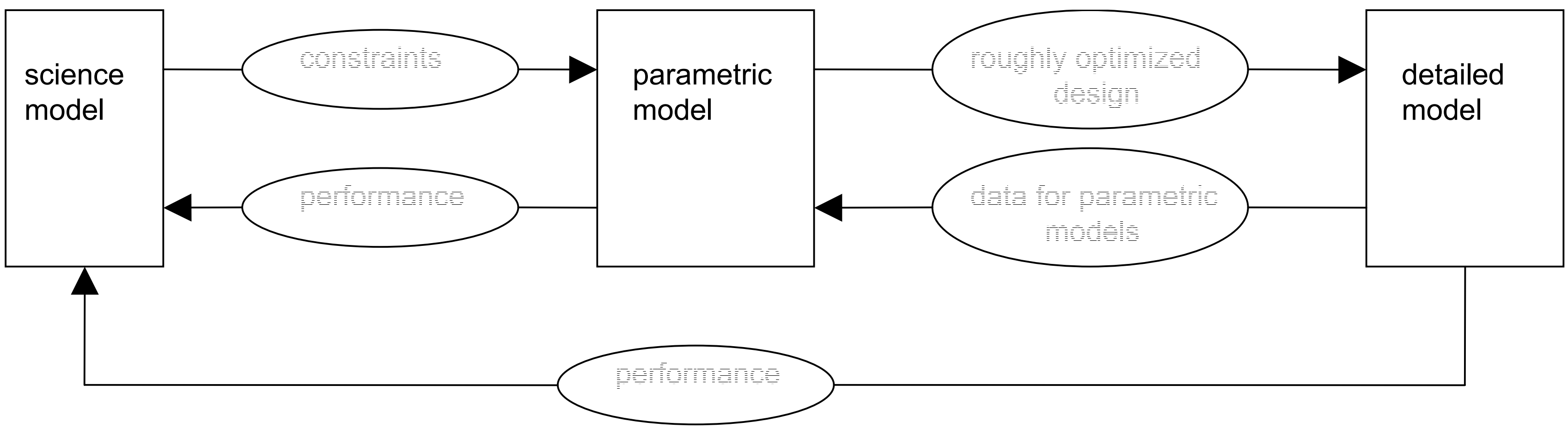
parametric model

1. low fidelity
2. wide field of view in design space (well-matched to science model)
3. simple & fast
4. perturbation analysis calibrated using point design(s)

detailed point design

ray tracing – optical performance
FEA – deflections, vibrations
CFHD – wind
WBS – cost & schedule

e.g. focal ratio, segment size, secondary support stiffness, control bandwidths



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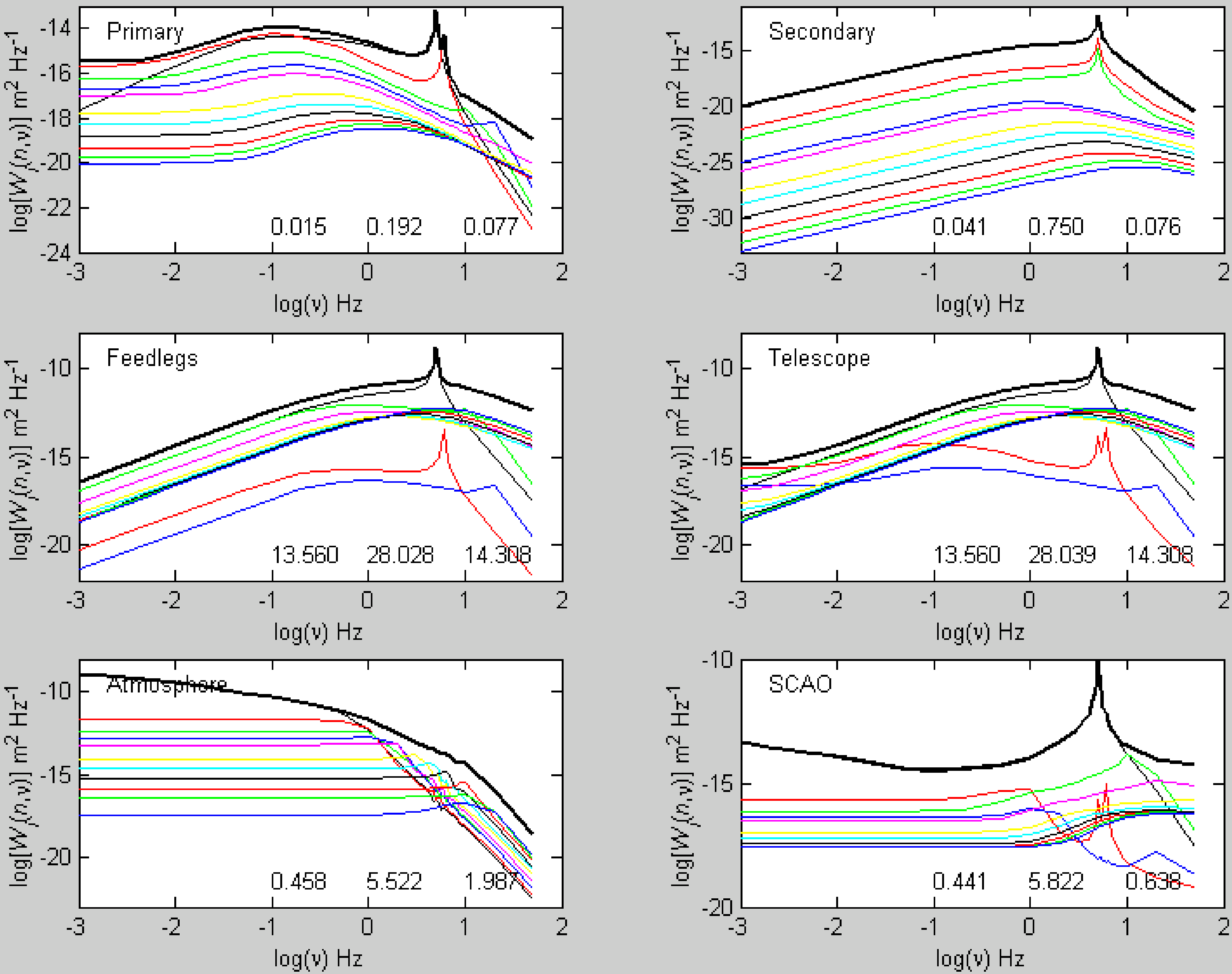
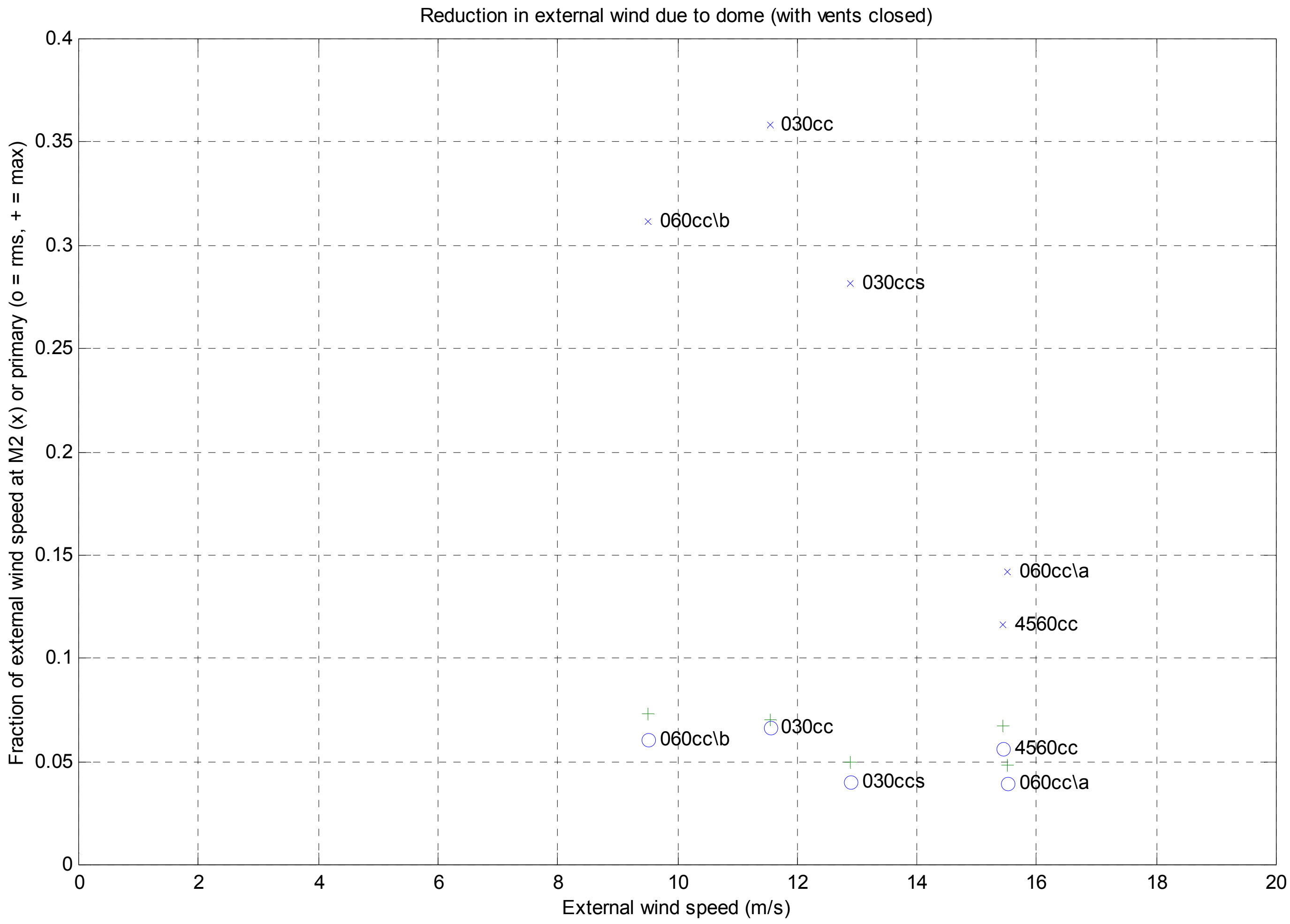
CoM



numbers - image diameter (arcsec), rms wavefront error (μm), rms wavefront error for *n* >1 (μm)

Gemini South measurements of wind speed

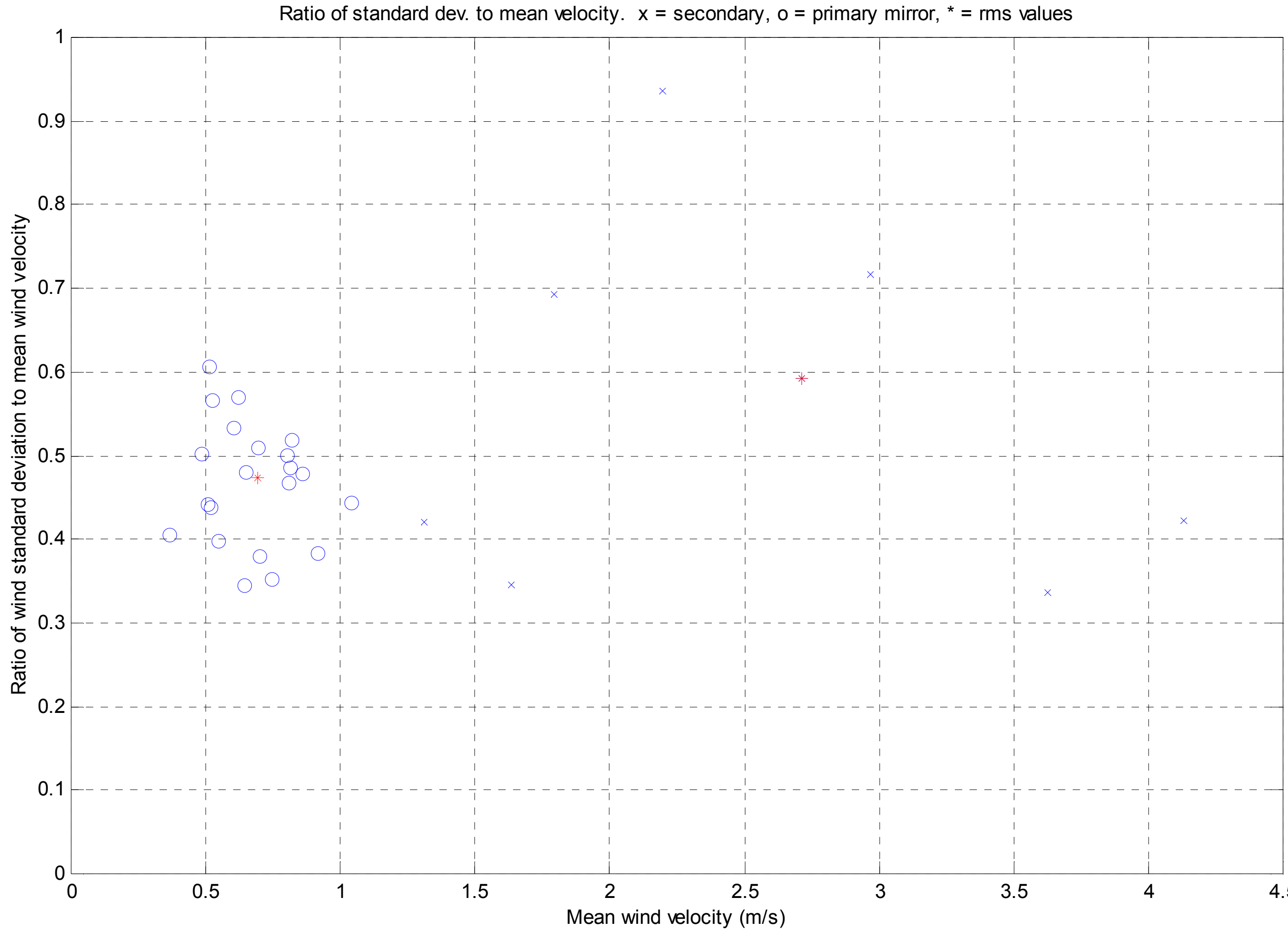
from D. MacMartin "Conclusions from Gemini Wind Data"



Reduction in external wind speed: x for secondary , o for rms at primary, and + for peak wind speed at primary. Case numbers next to data points are 0 or 45 for azimuth, 30 or 60 for elevation, and "cc" to indicate both vents closed. 030ccs also has windscreen.

Gemini South measurements of mean & rms wind speed

from D. MacMartin "Conclusions from Gemini Wind Data"

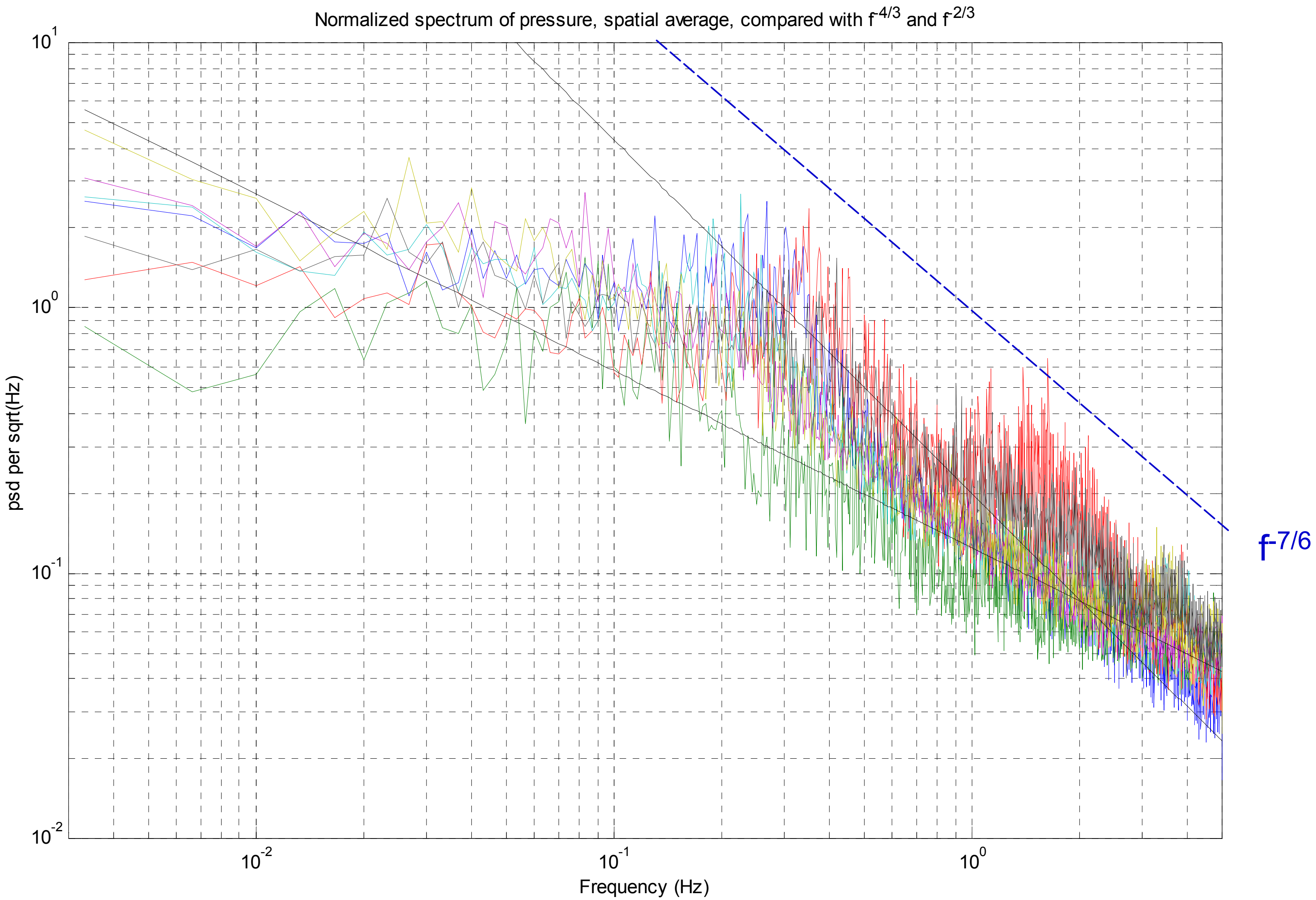


Ratio of standard deviation of wind speed to mean wind speed , at secondary (x) and primary (o), and rms values (*).

At both primary & secondary, rms wind speed ~ 0.5 x mean wind speed

Gemini South measurements of pressure spectra

from D. MacMartin “Conclusions from Gemini Wind Data”



If $L_0 = R_p = 4$m, and $u_p = 1$ ms^{-1}, $f_0 = 0.25$ Hz

For fully-developed turbulence, expect PSD(Hz$^{-1/2}$) ; $f^{7/6}$ at high frequencies

Parametric modeling of the CELT

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Simple models which capture trends in performance, cost & risk.
- fairly wide view of the design space, but with limited fidelity.

Current focus is on telescope dynamics (particularly wind).
- complements the work done in the conceptual design.

Goal is a top-level model of performance & cost for the telescope & enclosure.

Why bother with a formal, top-level, end-to-end parametric model?

Design trade-offs can be made early based on an overall view of the project

1. Cost control
   Parametric modeling provides a roughly optimized starting point for more detailed design. This reduces iterations of the expensive & time-consuming detailed design process.

2. Field of view
   The design space is large, but the high cost of detailed designs limits exploration. A parametric model allows a much broader view.

3. Checks
   Estimates from a parametric model provide a useful check on detailed model results.

4. Risk & contingency
   A parametric model can include risk, so it is possible (though not easy) to include risk management from the very beginning of the project.

But, a parametric model has limited fidelity, so it is most useful for a perturbation analysis based on a point design.