From Predictive Calibration to Forward Analysis

Preparing for the ELT era

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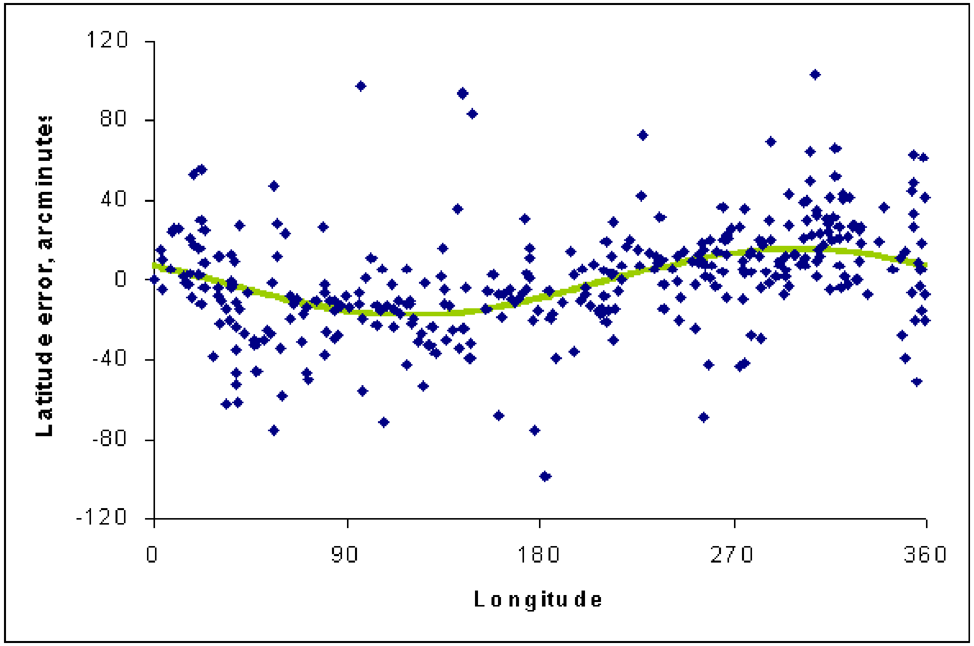
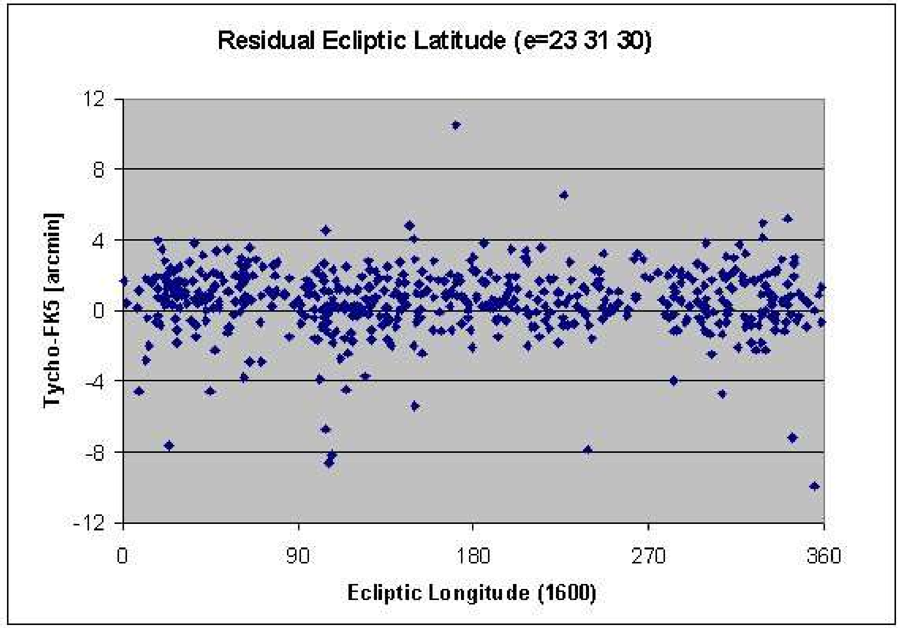
ESA/ESO

Hipparchos → Ptolemaios → Tycho





Tycho's Strategy

- **Be Better / Advanced in *ALL* areas of concern**

- **Suite of much better Instruments** **VLT/ELT**

- **Rigorous Calibration Plan**
  - Nightly cross-calibration / Frequent base checks **CalPlan, Std. Progr.**
- **Data Quality Check + Pipeline** **DQ + DF**
  - Usually at night spheric. trigon. results within 1 hr to check
  - "Pipeline" to solve ~ 50 000 spherical triangles
  - Logarithms not yet invented !! Need sub - " accuracy
  - So – Tycho invents "Prostapharesis" **predictive calib / forward analysis**

Agenda

- **Key Points**
  - Keeping the pace between upgrades of
    Scientific Aims (Ambitions) , Instrumentation and Methods
  - Consolidating ground conquered
  - Preparing for greater challenges

- **Key Phrases Predictive Calibration & Forward Analysis**
  - Predictive: utilizing physical (first) principles "a priory knowledge"
  - Forward: do justice to the (precious raw) "observables" by enabling to map into and compare theoretical models of targets in the raw data domain

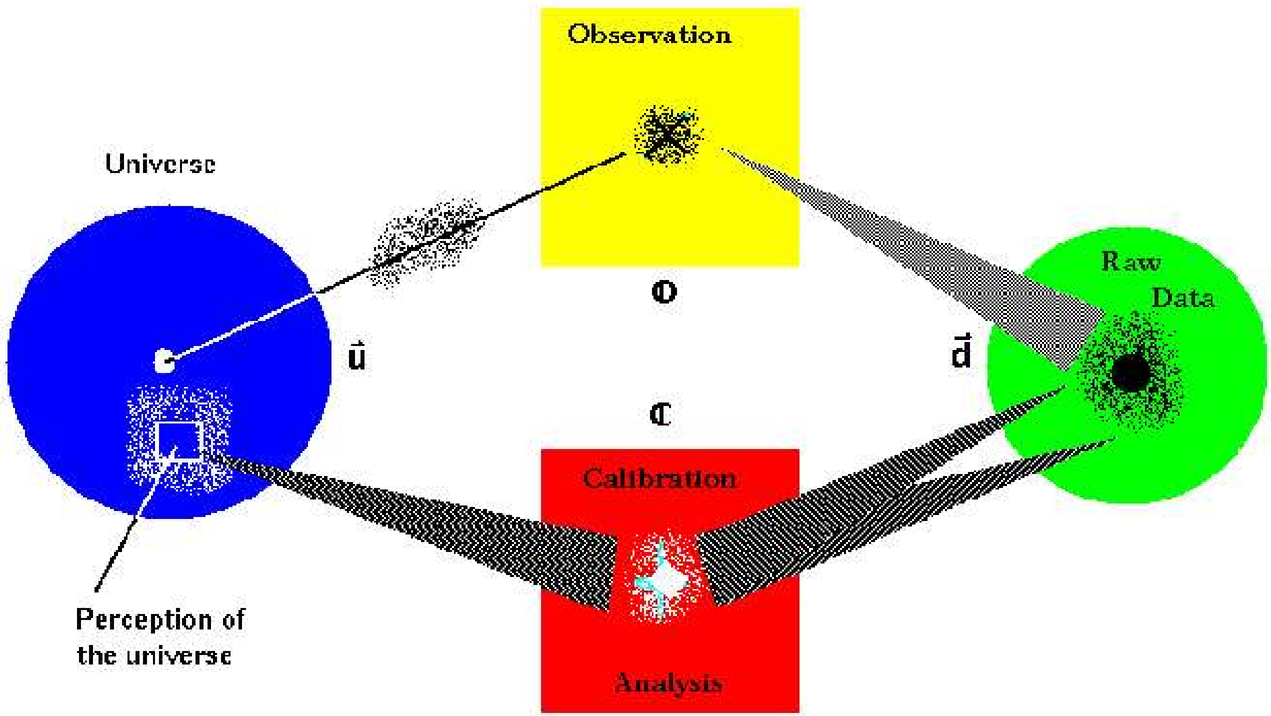
Heritage 1

- **1995 ST-ECF / ESO Calibration WS**
  - "Predictive Calibration based on Physical Instrument Models"
- **In parallel (→ 1998) ESO formulates**
  - VLT Operations Plan → Requirements for "Data Quality & Flow"
- **1997 - 1999 implementations of Physical Models**
  - CASPEC + UVES (Ballester & Rosa 1977 theory paper)
  - UVES W-Calib Bootstrap + more in ETCs (Ballester + team)
  - HST FOS (initially Rosa & Kerber)
- **1999 ESA → Instrument Physical Modeling Group**
  - thanks to former DG Riccardo Giacconi (see AnnRevAstrAstroph 2005)

Heritage 2

- **2000 - 2005 ST-ECF Team on FOS & STIS**
  - Alexov, Bristow, Fiorentino, Kerber, Rosa + contr. Modigliani (DMD)
  - FOS Post Operational Archive - based on FOS model
  - STIS Model + SimulatedAnnealing - demonstrated factor 10 +
  - Veryfied on superior entirely new Pt-Ne/Cr line catalogue (NIST collab.)
- **2005/6 CRIRES / Xshooter model**
  - Bristow + Kerber integrated into to ESO-INS
  - thanks to DG Catherine Cesarsky (bringing them back from ESA)
- **2007 → Physical Models established Instr. Support**
  - Spectrograph kernel + Simulated Annealing ready to …
  - … support many more spectrographic instruments

The Observational Information Loop



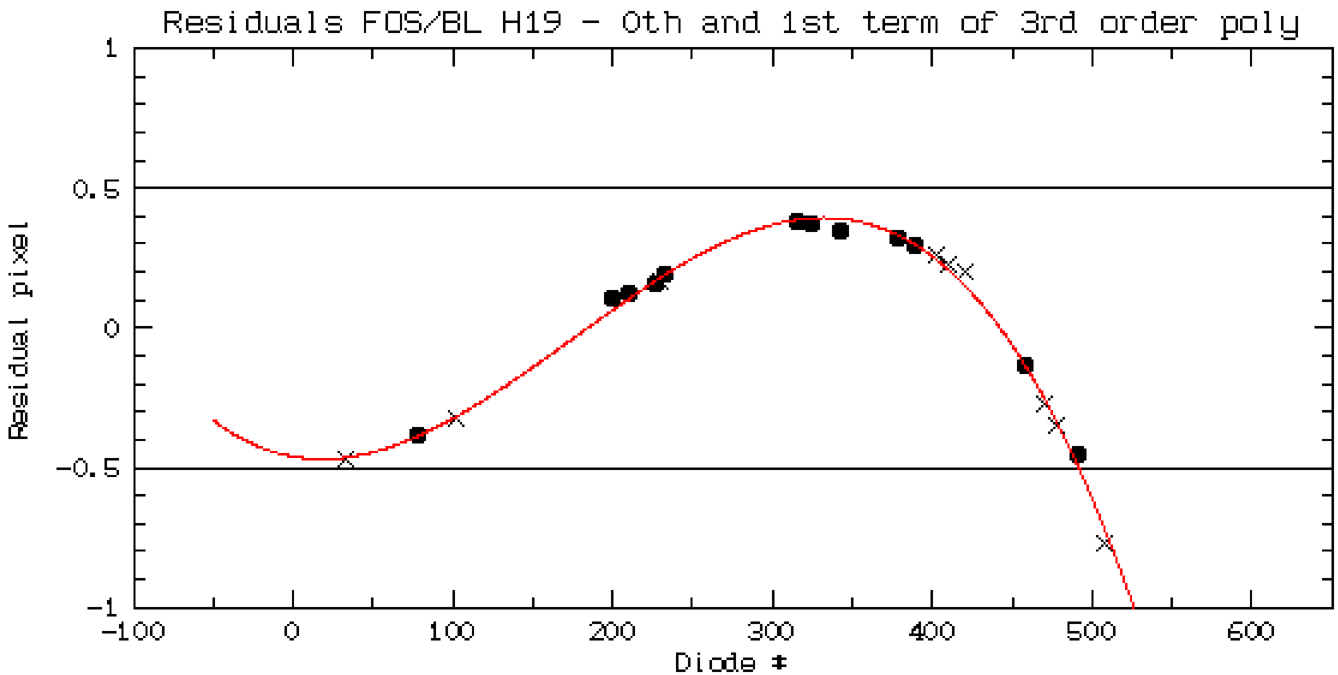
$\mathbb{O} \times \mathbb{C} = \mathbb{1}$??

Demonstration Case

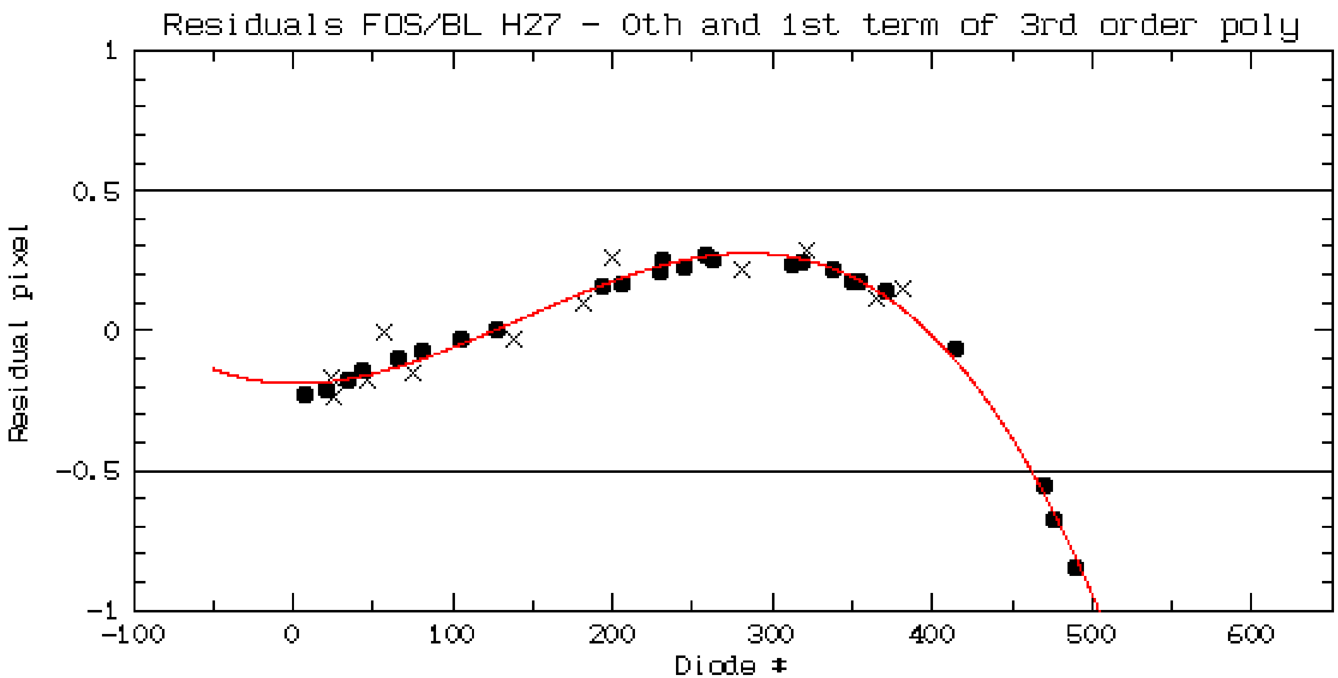
- **HST Faint Object Spectrograph (FOS)**
  - Relatively straight layout
  - Easy to grasp impact of "physical insight" on calibration
  - Obvious projection to FORSes …

- **Case STIS (UVES, CRIRES, XShooter…)**
  - More complex (2D – echelles, multi-objects…)
  - But also "done" (in principle …)

3rd order Poly - Dispersion Relation



3rd order Poly - Dispersion Relation



FOS Dispersion Model - Physical Principle

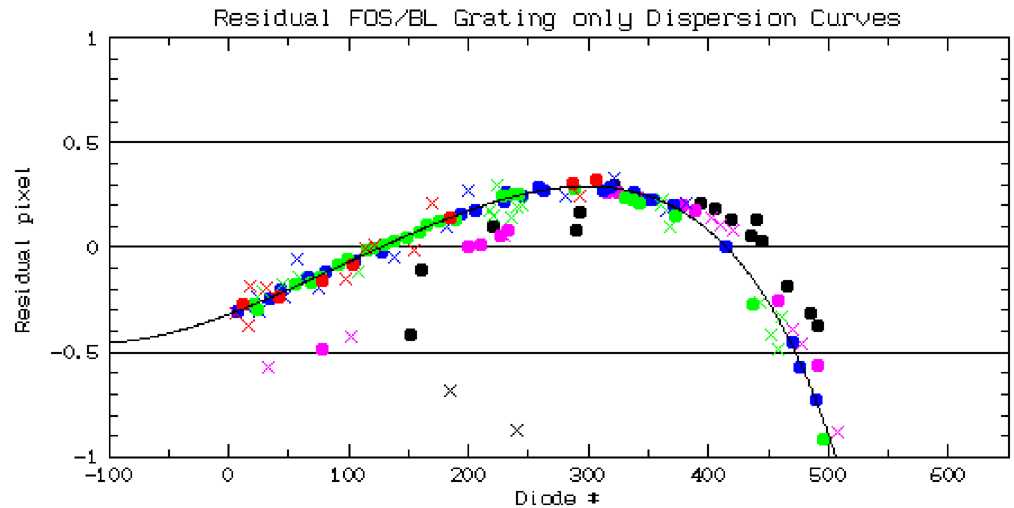
- **Relevant FOS Optical Layout in High Res Mode**
  - wheel holds 5 different 1st order spherical gratings, 4 used per detector
  - Imaged onto blue/red channel Digicon tubes

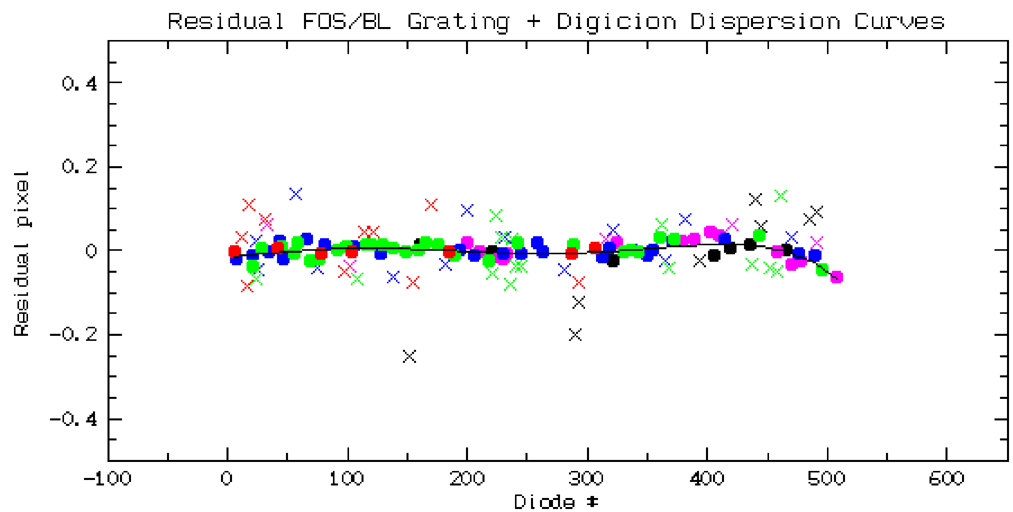
- **Physical Principles**
  - ray optics equation from grating to photocathode
  - $z = (f - f_0) * [\ \alpha + \beta + \arcsin\{\ s / m * \lambda - \sin(\alpha - \beta)\ \}\ ] - z_0$
  - S-distortion in Digicon tube (off-axis aberration in E x B geometry)
  - $x = g * z + h * \tan(i + j * z) - x_0$

- **Restrictions on Parameters**
  - common to all gratings on a given detector: z0 , x0 , *g* , *h* , *i* , *j*, *f0*
  - common to the red and blue channel per grating: f, $(\alpha - \beta)$, $[s / m * \lambda]$

FOS Dispersion Model

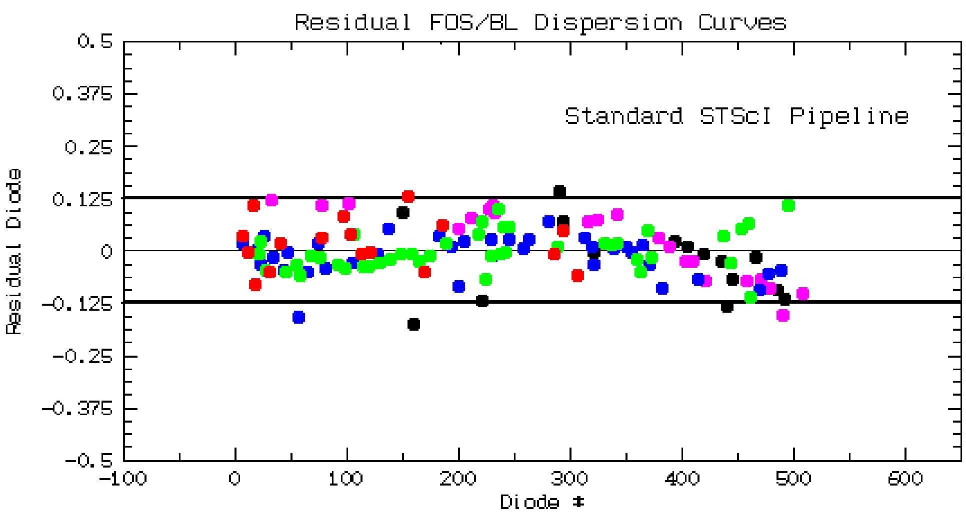
- **Result (FOS BLUE)**
  - Assume that S-Distortion common to the 3 clean library list modes valid for NUV/FUV as well
  - Optimize common solution including the S-Distortion
  - Final residuals below 0.1 pix amplitude
  - Common pattern to all modes is pin-cushion distortion

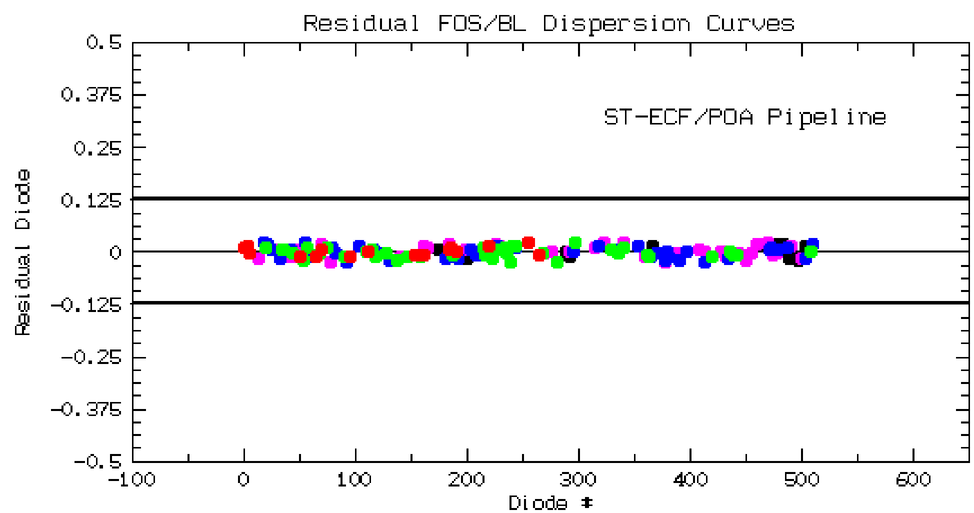




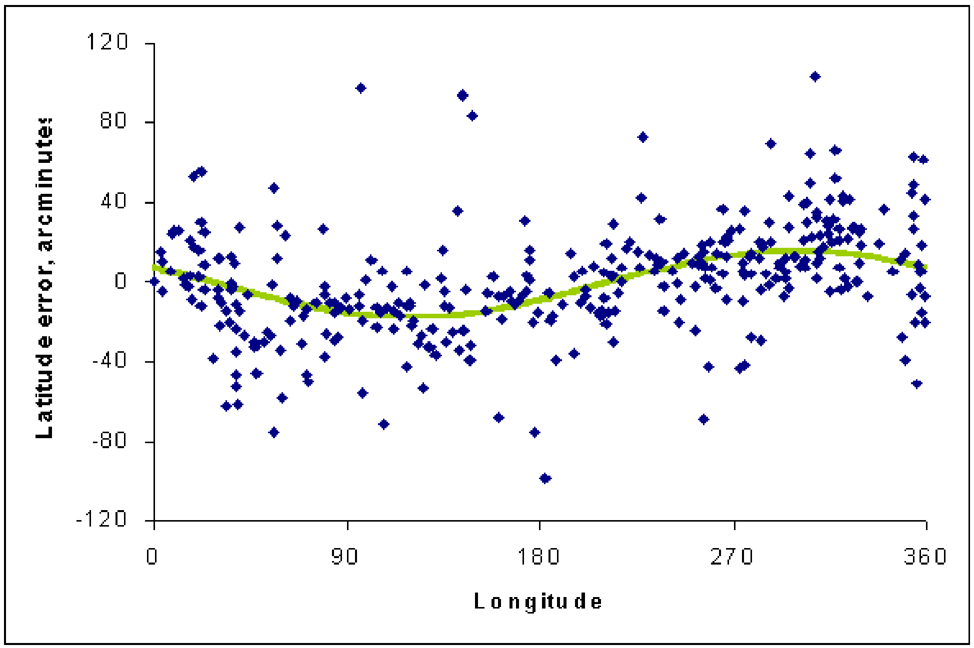
Dispersion Relations for FOS

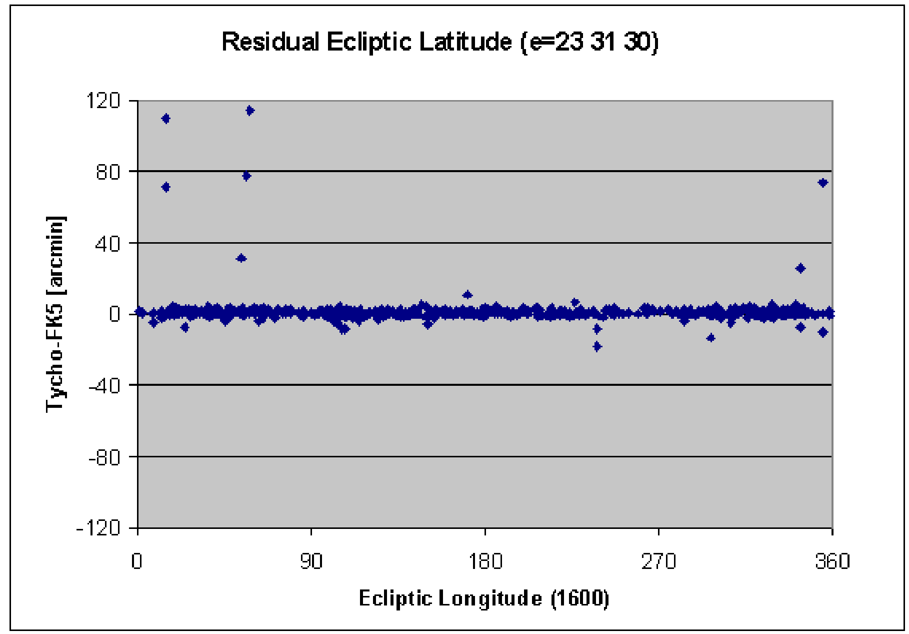
- **Shown are residuals measured w.r.t. model solution**
- **FOS Dispersion Model valid for all gratings (differing colors)**
  - mode specific parameters: only grating constant, grating angle
- **Classical polynomial fit will fit all lines well**
  - whether or not they are blends, wrong identifications, too sparsely spread





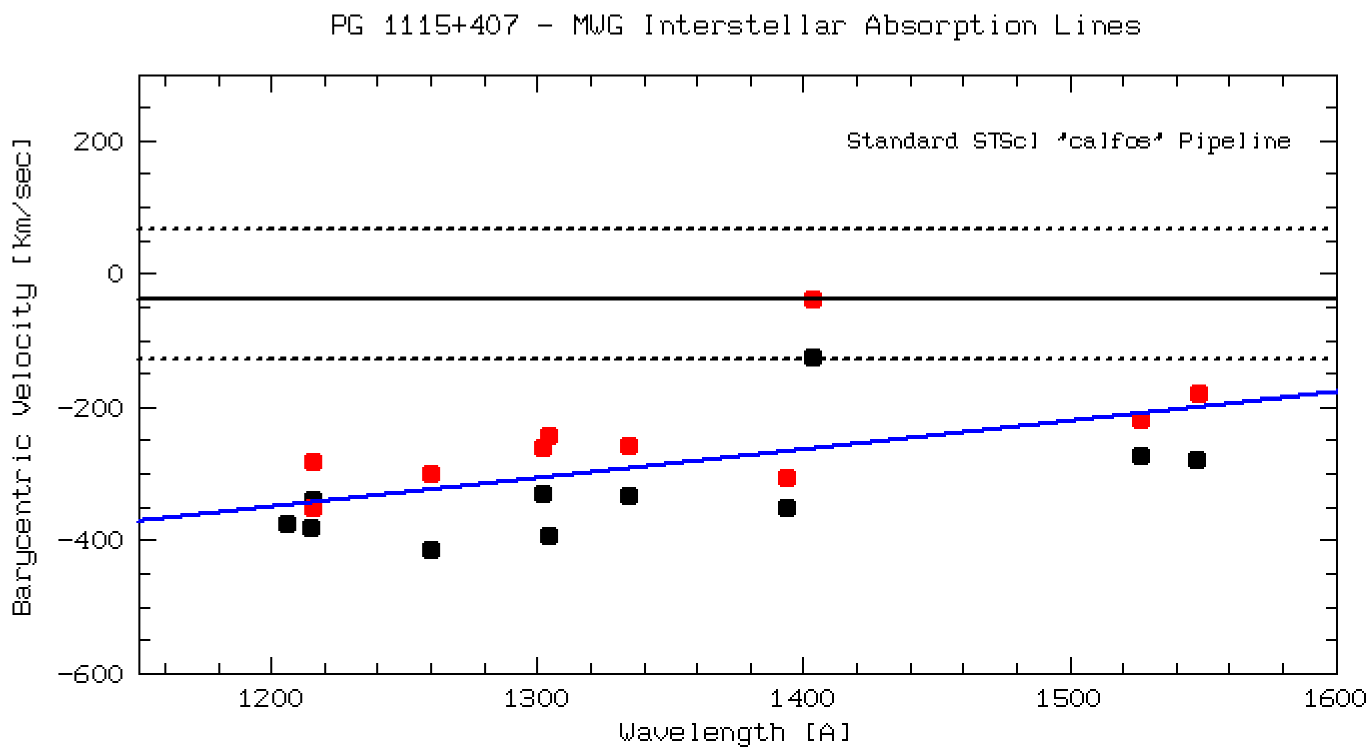
Hipparchos → Ptolemaios → Tycho





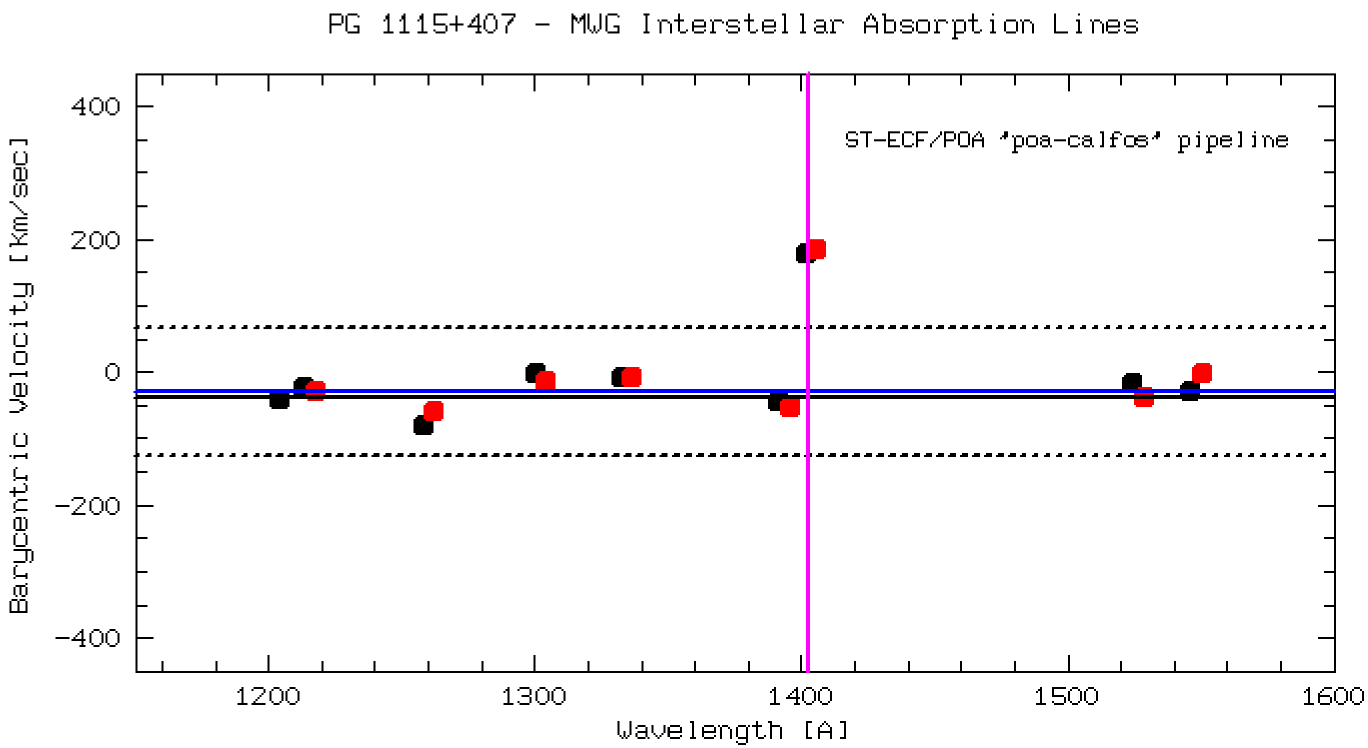
MW Halo absorptions in QSO spectrum
Standard “calfos”

- 2 long exposures (blk,red) show repeat error
- Unphysical dependency of velocity on wavelength
- Only one absorption at 1403 A seems to fit expectation



MW Halo absorptions in QSO spectrum improved with “poa_calfos”

- POA GIMP correction minimizes repeat error from 2 long exposures (blk, red)
- All but one line match central value of expectation (21 cm line)
- The one not fitting now is QSO Ly alpha redshifted (= NEW science)
- Result of POA GIMP correction in combination with physical model dispersion

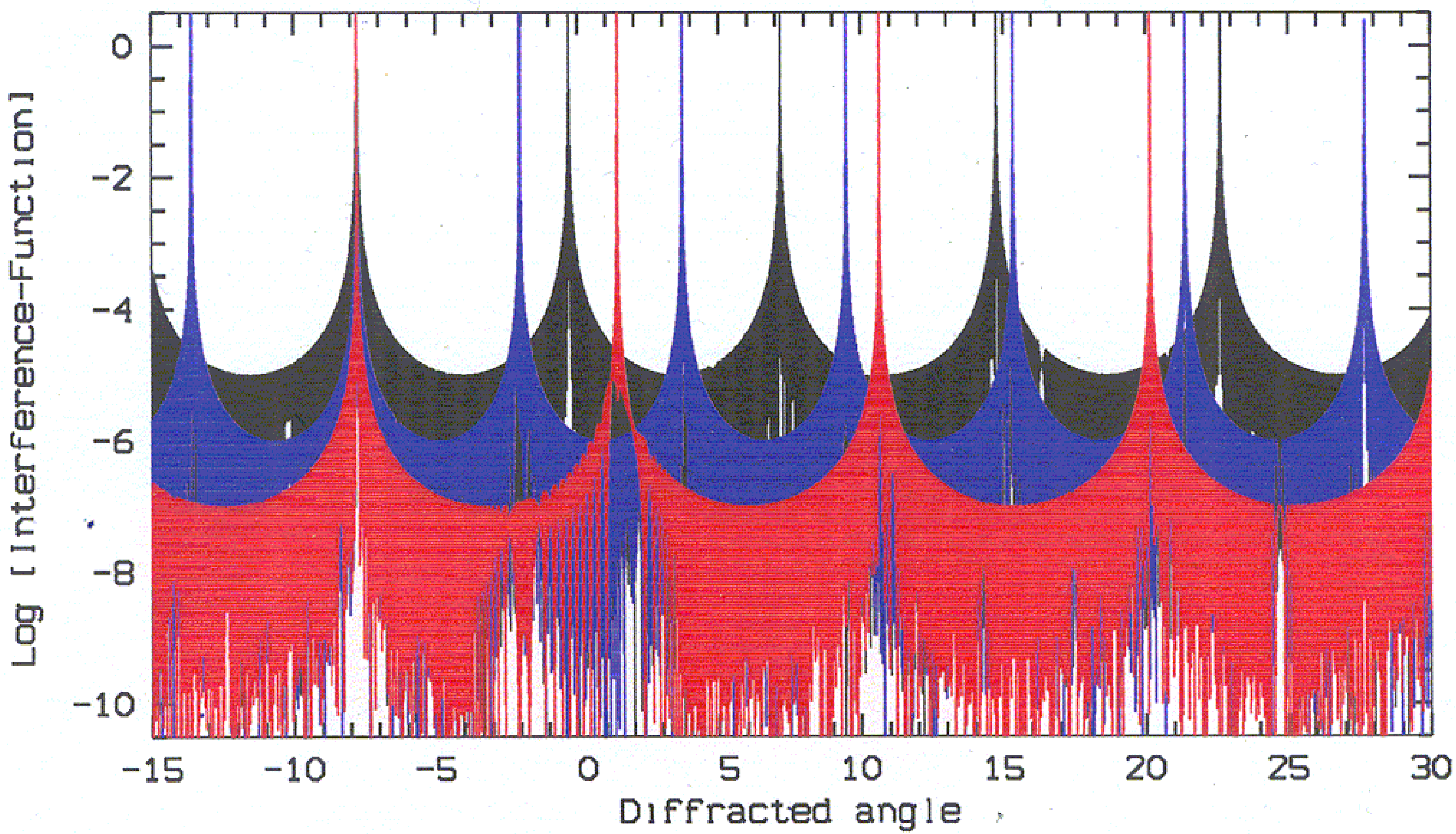


What about Flux Calibration

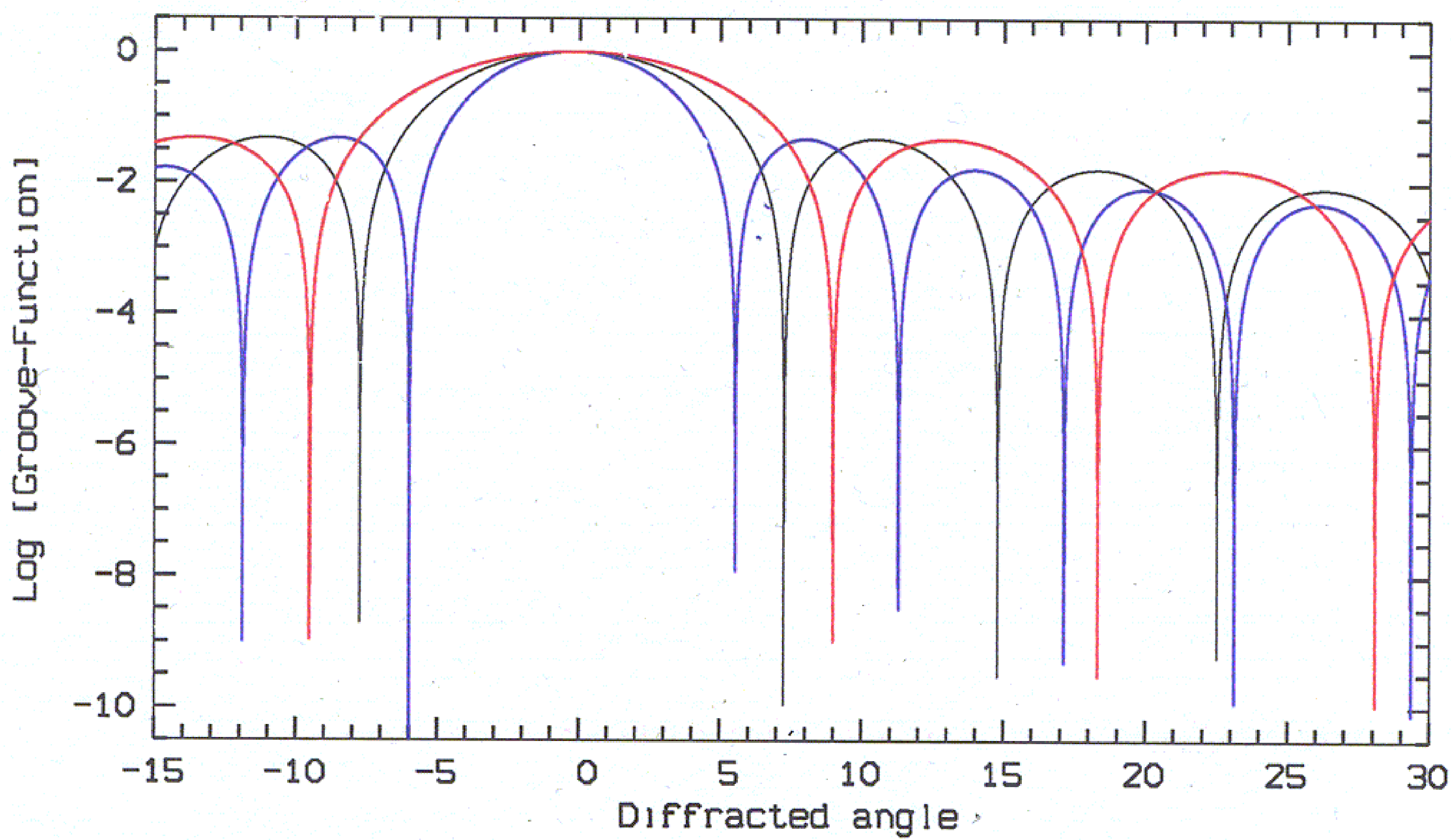
- **PM should only predict Blaze-Function**
  - Vignetting(s) will follow from optical path model
  - Mirror reflectivities etc. will enter as (accurate) laboratory measurables but are allowed to change as required by insight (measurement)
  - Combined model will be tuned so that StdStar comes out correctly

- **That is**
  - PM predicts the SHAPE of the flux calib curve
  - SCALING is the business of on-sky calibration (zero-points)

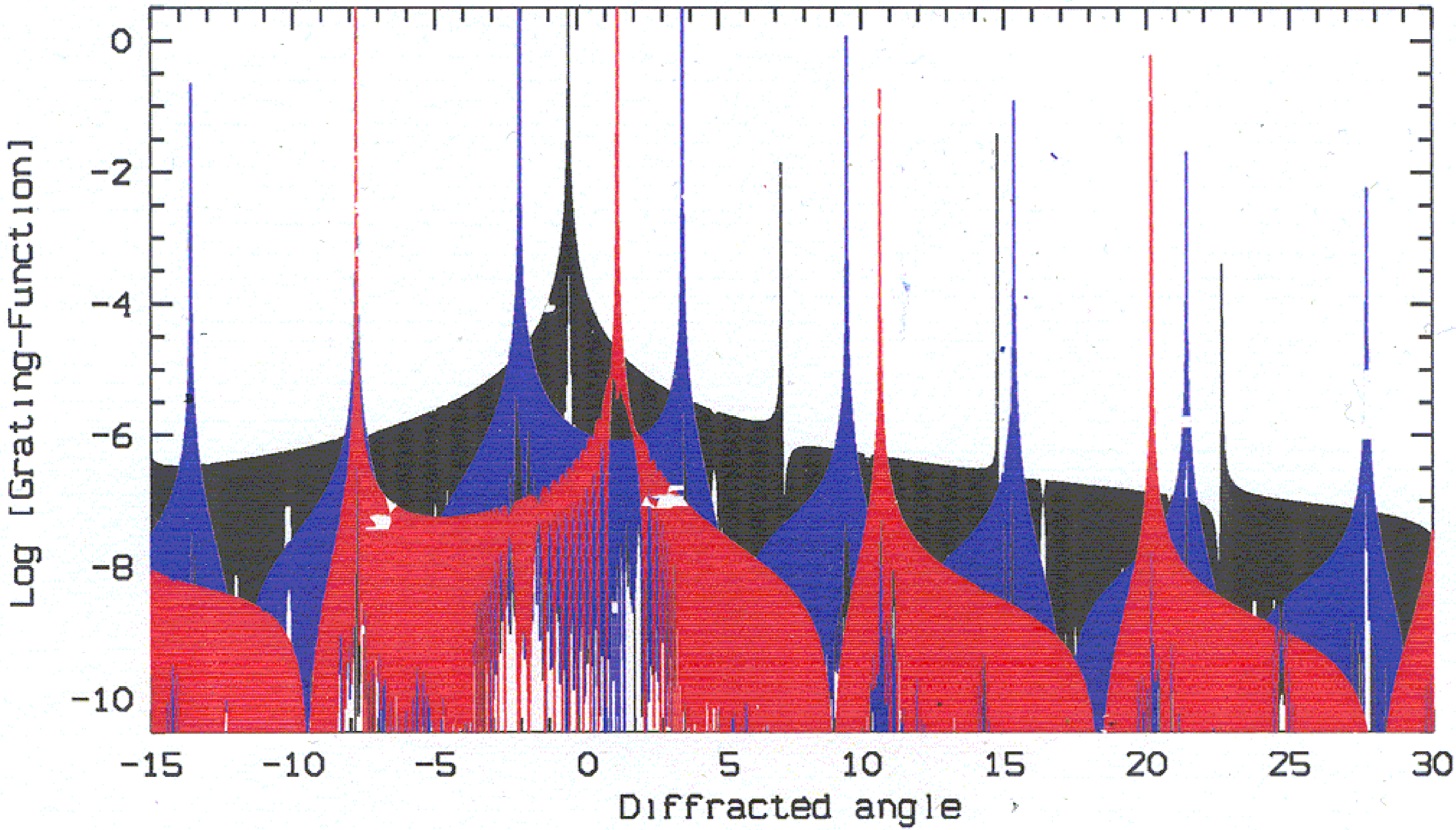
Grating - Interference



Grating - Diffraction



IF * DF

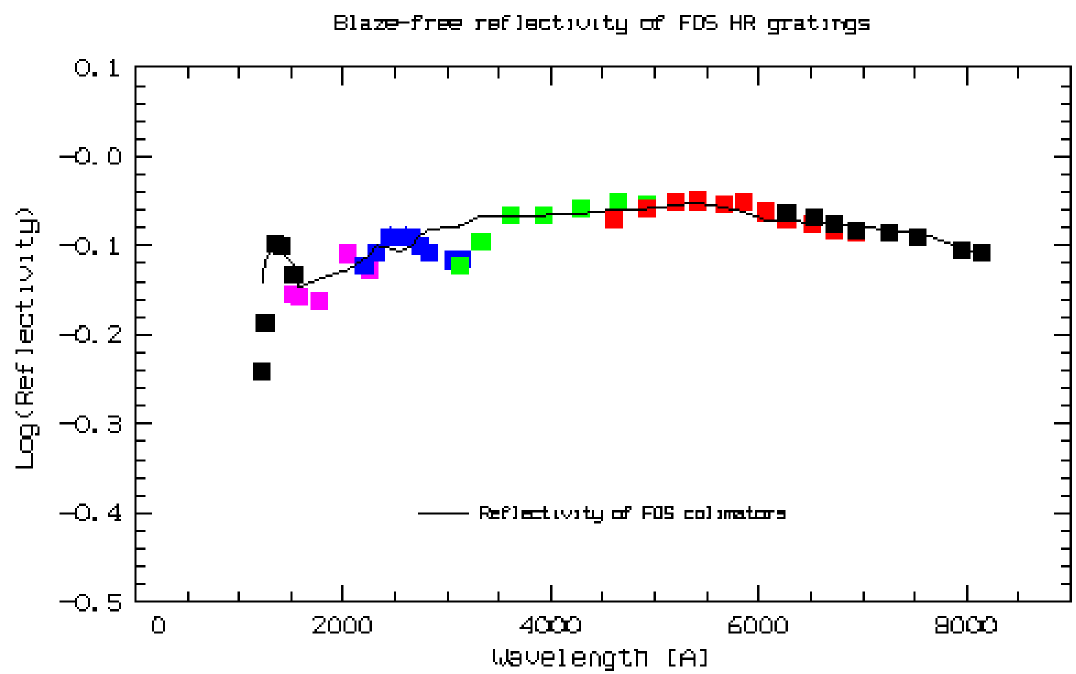


Log [Grating-Function]
0
-2
-4
-6
-8
-10
-15
-10
-5
0
5
10
15
20
25
30
Diffracted angle

FOS Model - Prediction for Blaze

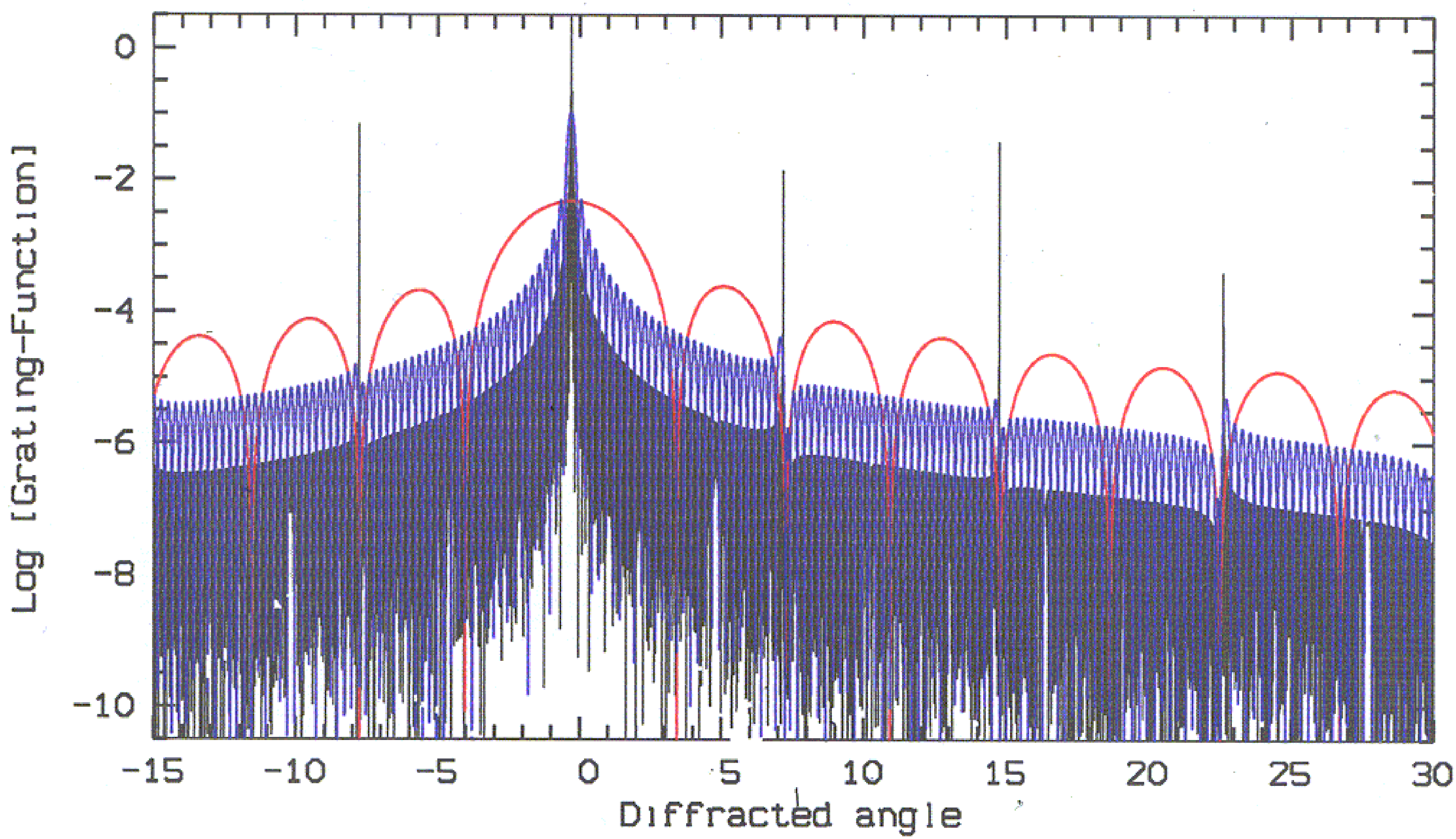
- **Predictive Power !!**

- **Blaze-Free Efficiency**
  - should be the coating
  - IF*DF @ peaks in 1st order = efficiency as $f(\lambda)$
  - predicted sensitivity (-HST)
  - compare to empirical flux cal
  - derive blaze free efficiency

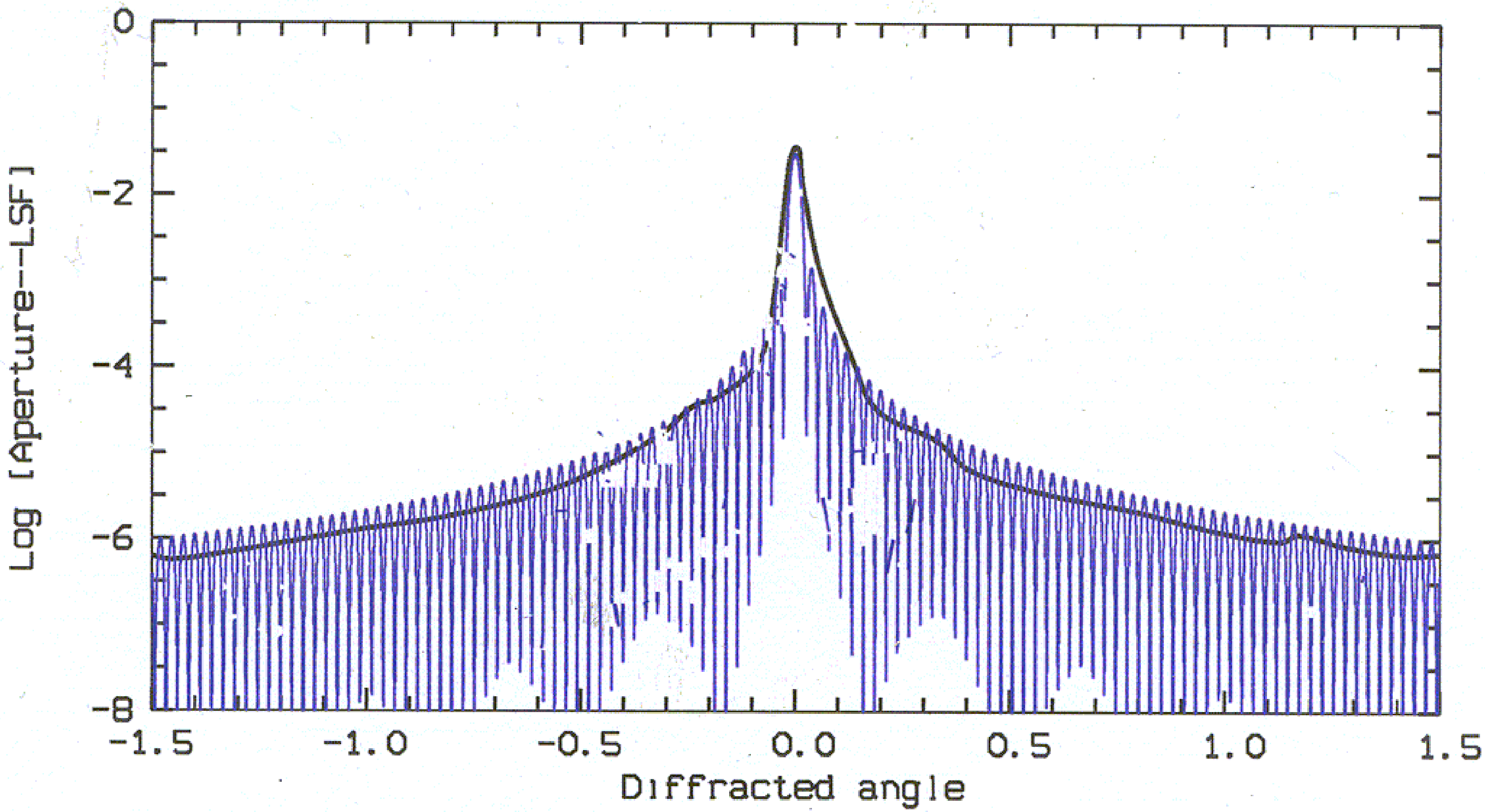


- **Standard Stars wrong !!**
  - FUV/NUV/opt joints ~ few %

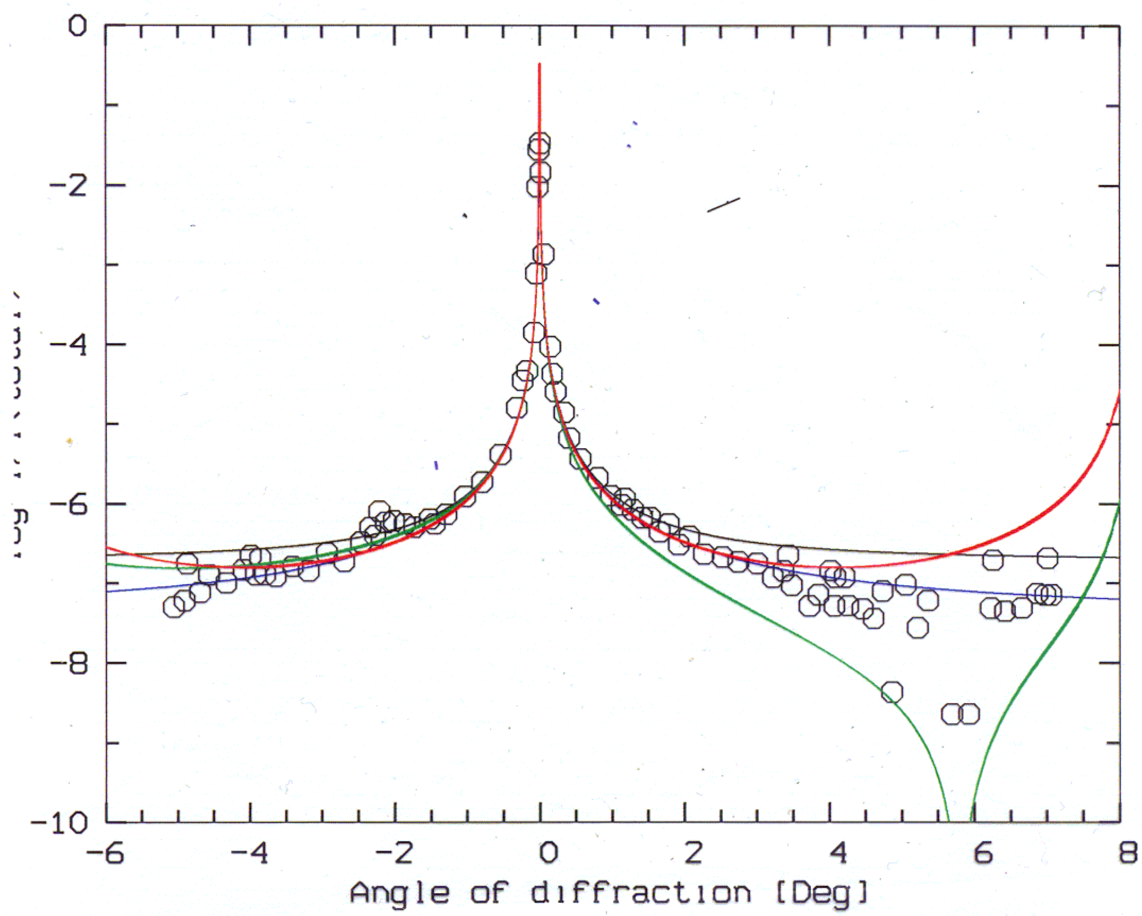
Line Profile - IF * DF (slit+collimator)



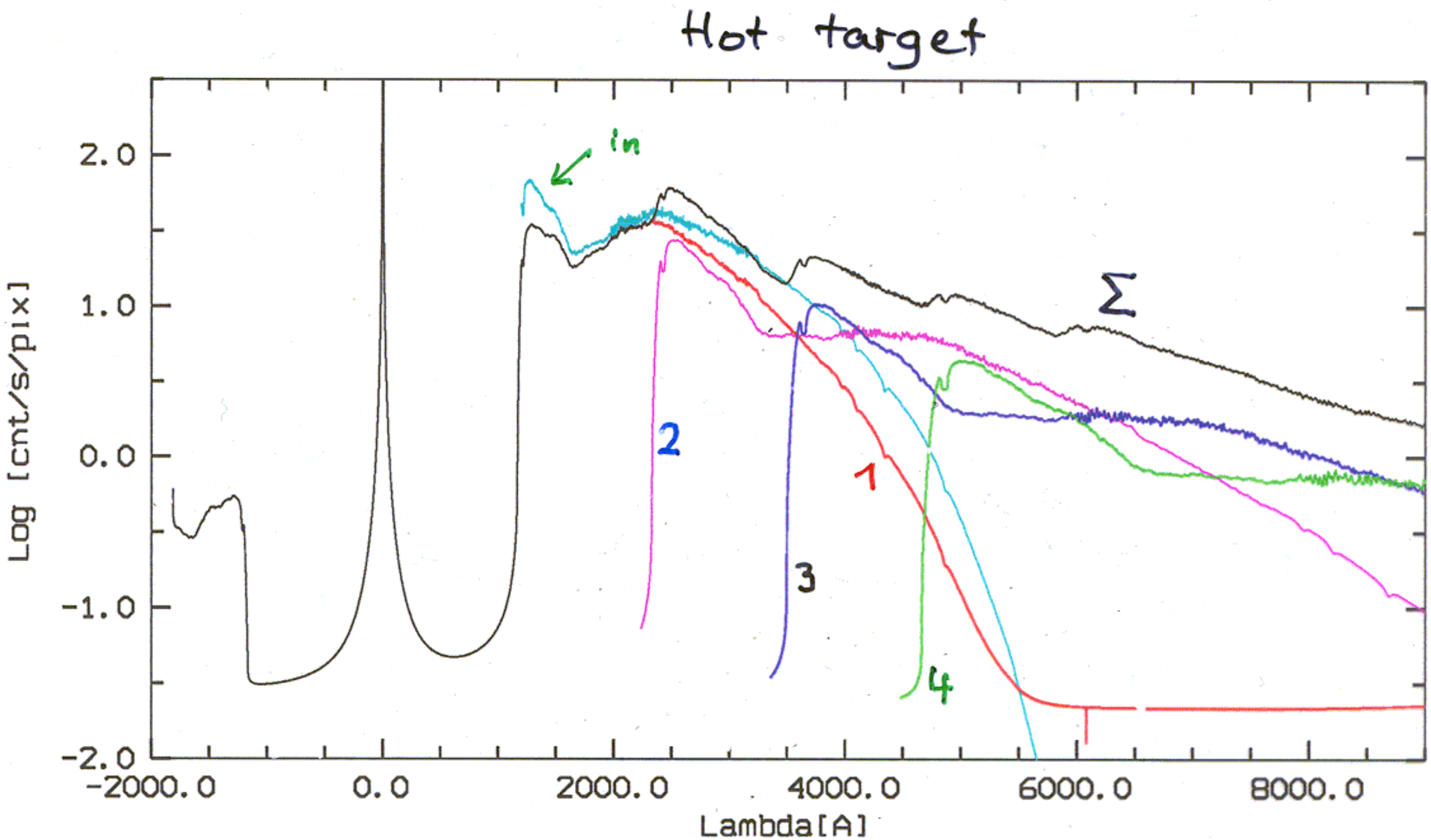
Line Profile - obs vs theory (-vign)



Line Profile - obs vs theory (2)



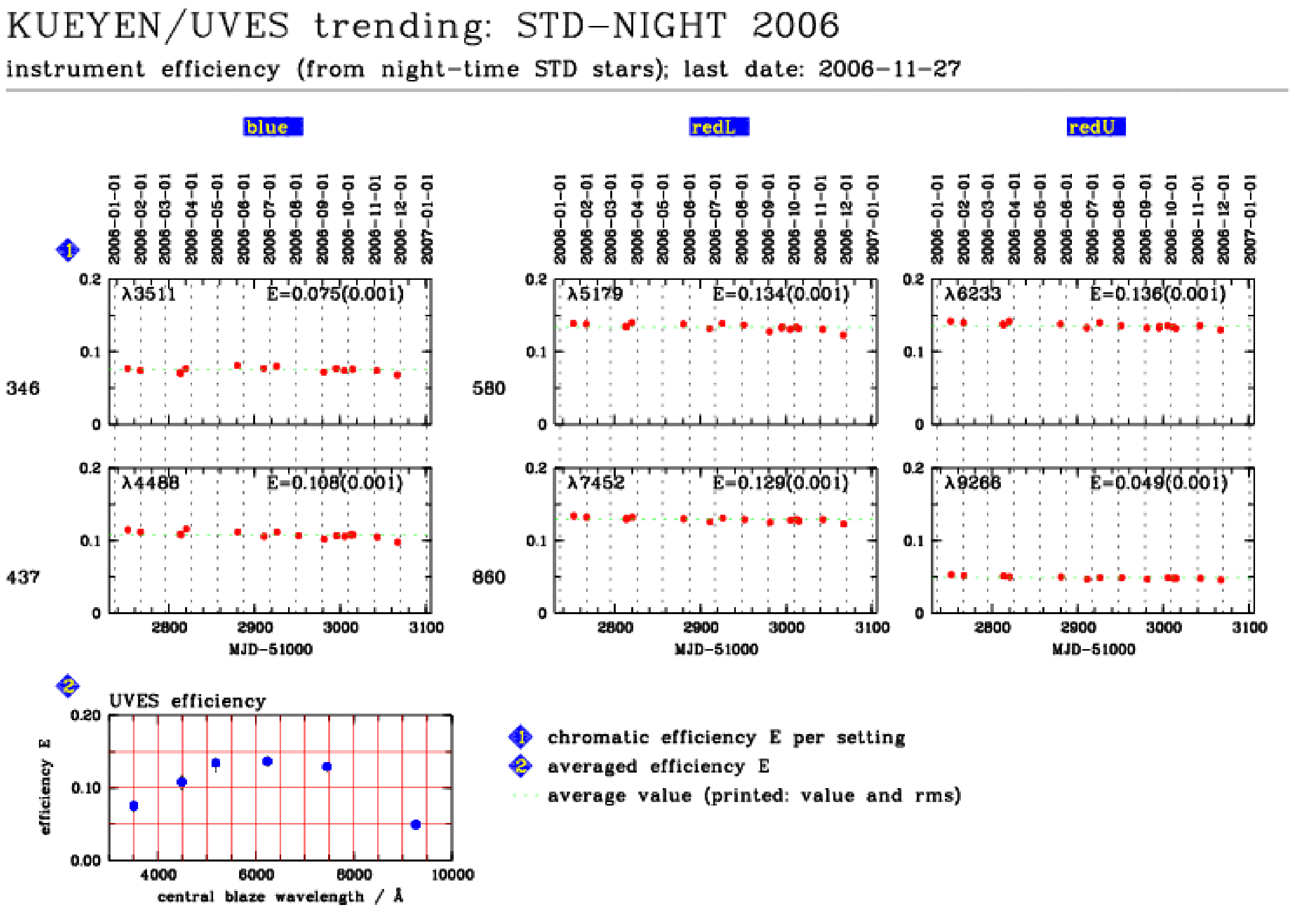
Full Throughput Model - Hot Target



Roadmap

- **Very many "Observatory" pieces already in place**
  - Cal Plans , DQC and data base
  - Know how of "how to deal with data" (extraction, peculiarities)
  - Build up of extensive data base on detector performance
- **Know how, building blocks for "PhysModels" + Lab Standards**
  - many individuals already carry parts of the "company knowledge"
  - Parts of original IPMG integrated into ESO-INS (Bristow, Kerber)
  - PhysMod based calibration part of CRIRES and XShooter Projects
- **Required: Consolidation – Sustainability - Development**
  - Critical review of reference data and processes
  - Clearing station to achieve coherent view
  - Injection of advanced calibration concepts into instrument design

Stability of Instruments



Yes, agreed in principle, but …

- **Non-stability of instruments on ground**
  - PM strengths → meaningful parameters → insight
  - and see DQC trending → eg. UVES, FORSEs usually very stable
- **On ground we have an atmosphere**
  - PM strengths → decoupling of instr. / atmosph. effects
  - Atmosphere becomes a separate “controllable” item
- **Our instruments are too complicated**
  - we designed them, so we have the insight
  - more complex → more substantial insight helps

Atmosphere (terrestial)

- **Key: Separate Instrumental Stuff from Atmosphere**
  – Required: PhysMod based Calibration

- **Atmosphere - becomes another “model item”**
  – At least from 320 to about 850 nm (the DoD knows that also beyond)
  – Extinction → 3-4 components → Form well known
  – Actual scaling should be controlled by LOSSAM / Std.Star expos

- **Sky Brightness - calls for a scaleable model as well**

  → F. Patat’s talk on Tuesday morning

Atmosphere (terrestial) cont.

- **b.t.w. - I'm proud that**
  - everyone observing LS or PO is using "ATMOEXAN.TBL"
  - I constructed it in 1983
  - by matching a 3 component **Physical Model**

    (Rayleigh, Ozone, Aerosols)

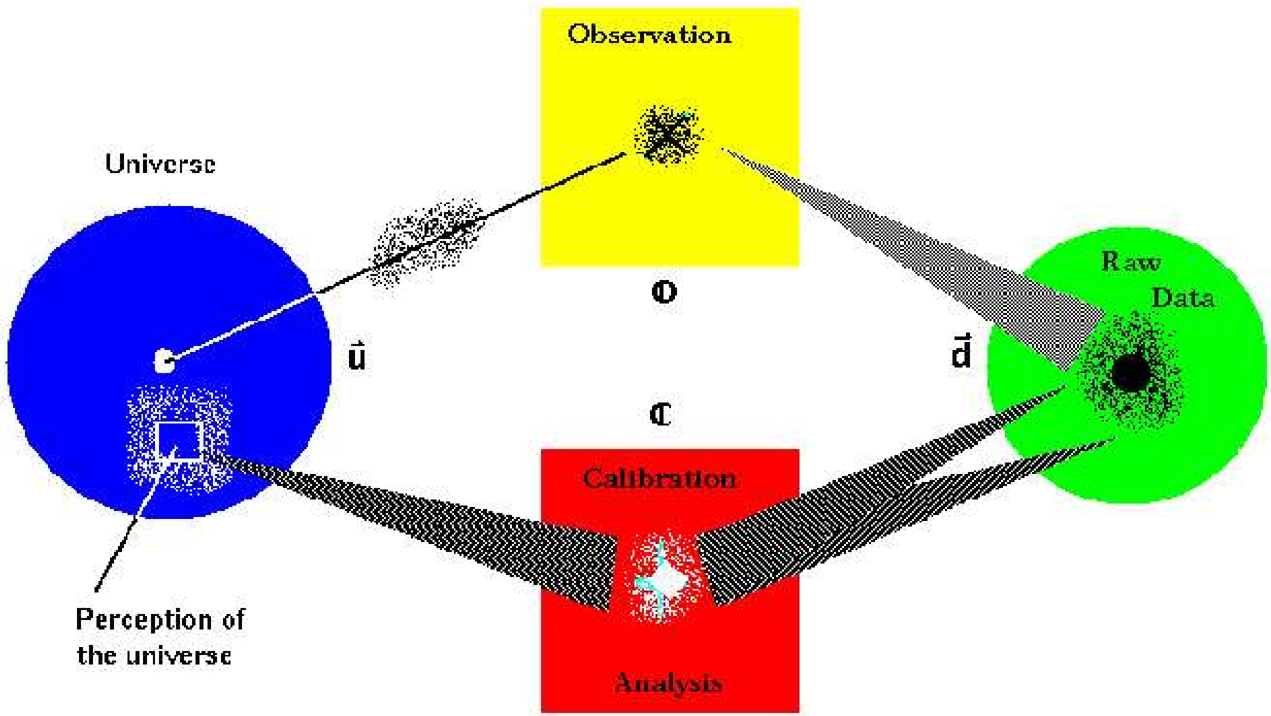
    … to the sparse data points of Tueg (1977 = Messenger 11)
- **But**
  - **Anyone ever checked it for PO** ? – it was for LS altitude !!
  - It does not include dust (Vulcanoes, Copper-Mining …)
  - Also, meanwhile we got "Globals" (Warming, Dimming etc …)

- So much for those that still pretend that

“ Physical Models can not be of much use
at a ground based observatory …
… because we have an Atmosphere.

Michael - you know, we prefer to use
good old ATMOEXAN instead ”

Reminder:
Observation Information Loop



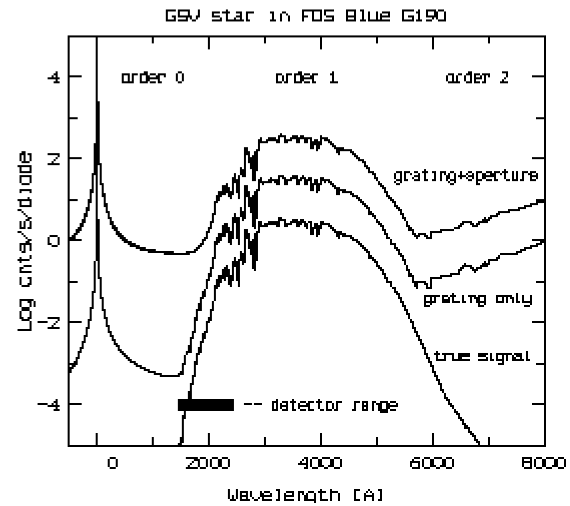
$\mathbb{O} \times \mathbb{C} = \mathbb{1}$??

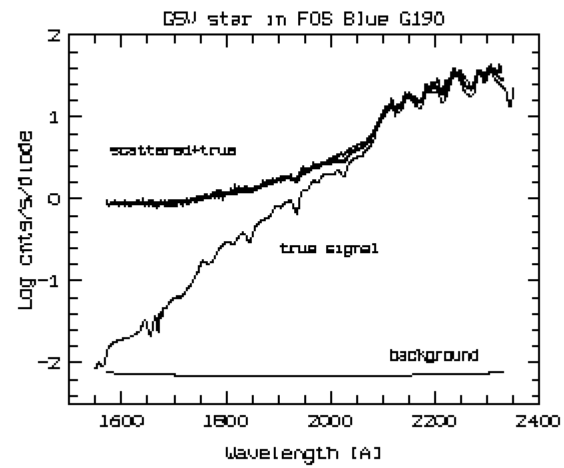
Definitions & Examples

- **First principle model** ***Ray trace spectrograph model***
  - prescription based entirely on physical laws
  - very high predictive power
  - required to isolate effects while building physical models
- **Physical model** ***UVES/STIS model (ray + dist.)***
  - prescription primarily based on physical / engineering insight
  - empirical "fudge" only as unavoidable (tolerable) substitute
  - sufficient predictive power for predictive calibration, forward analysis
- **Empirical model** ***ETC, polyn. dispersion fits***
  - no physical insight required / inserted , can not be inverted
  - no predictive power outside data range / when params change

FOS Scatter Model
Test on Data

- **Recall**
  - wanted to predict the observed raw data for a cool target at UV wavelengths
  - Test for a Solar Analog
  - pass Kurucz model of Sun through the FOS model
  - compare with observations of solar analog 16 Cyg B
  - @ 160 nm signal is 1% of scattered (red) light
  - still the prediction agrees to better 5 % with actual data





Concepts to Get Around the Info Loop

- **Canonical Concept** *Empirical backward analysis*
  - empirical calibration relations → re-scale raw data → interpretation
- **Advanced Concept** *Predictive Calibration*
  - instrument models → noise free calibration relations
  - first principles → predictive capabilities outside “standards” range
  - Analysis: like empirical concept → “backward” (scaled raw data)
- **Superior Concept** *Forward Analysis*
  - can simulate raw data with sufficient accuracy and detail
  - evaluate theoretical target models in raw data domain
  - obtain likelihood estimates for range of potential target properties

Calibration in Context

- **Determine relation between output and the value of the input quantity, a reference standard (ISO 9000)**

- **Traceability –** establish accuracy by an unbroken line to higher standards. For each step evaluate uncertainty.
- **Quality Control –** monitoring, stability
- **Data Reduction – or better "Preparation"**
  - removal of instrumental signatures, extraction, "resampling"

- **Why do Calib and Reduc appear to be so intermingled ?**

FOS Calibration Issues - Physical View

- Geometric and Physical (wave) Optics
  - dispersion relations — bad Pt-Ne/Cr line catalogue and polynomial fits
  - reflectivity, sensitivity, LSF, — grating scatter, blaze functions
- Electron optics (S-Distortion, GIMP, YBase trim)
  - x (dispersion direction) --> lambda zero points, flat field shifting
  - y (spatial direction) --> vignetting (=absolute flux scale), color terms
- Thermal, mechanical, electronic, environmental items
  - wavelength scale zero points (bending), flux scale (pointing, vignetting),
  - dark level (solar cycles, particles in geo B-field, unbaffled stray light)
  - Legend: good - to be considered - upgrade desirable - upgrade required