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Update and Status of the Aerospace Stellar Spectral Energy Distribution Catalog

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Background

- During the MSX – SPIRIT III program, careful attention was given to on-orbit absolute irradiance (point source) calibration
  - *Used models from Cohen, Walker, and Witteborn*
  - *Uncertainties were established from Aerospace Observations*
  - *Led to appreciation for need in the future for very high quality, uniform stellar reference spectral energy distributions based on data, not models*
  - *Models in IR do not cover all phenomena – especially dust and its effects, and variability*
    - Many of the brightest IR stars are variable, and not predictable
    - Requires high quality observing program, responsive to users

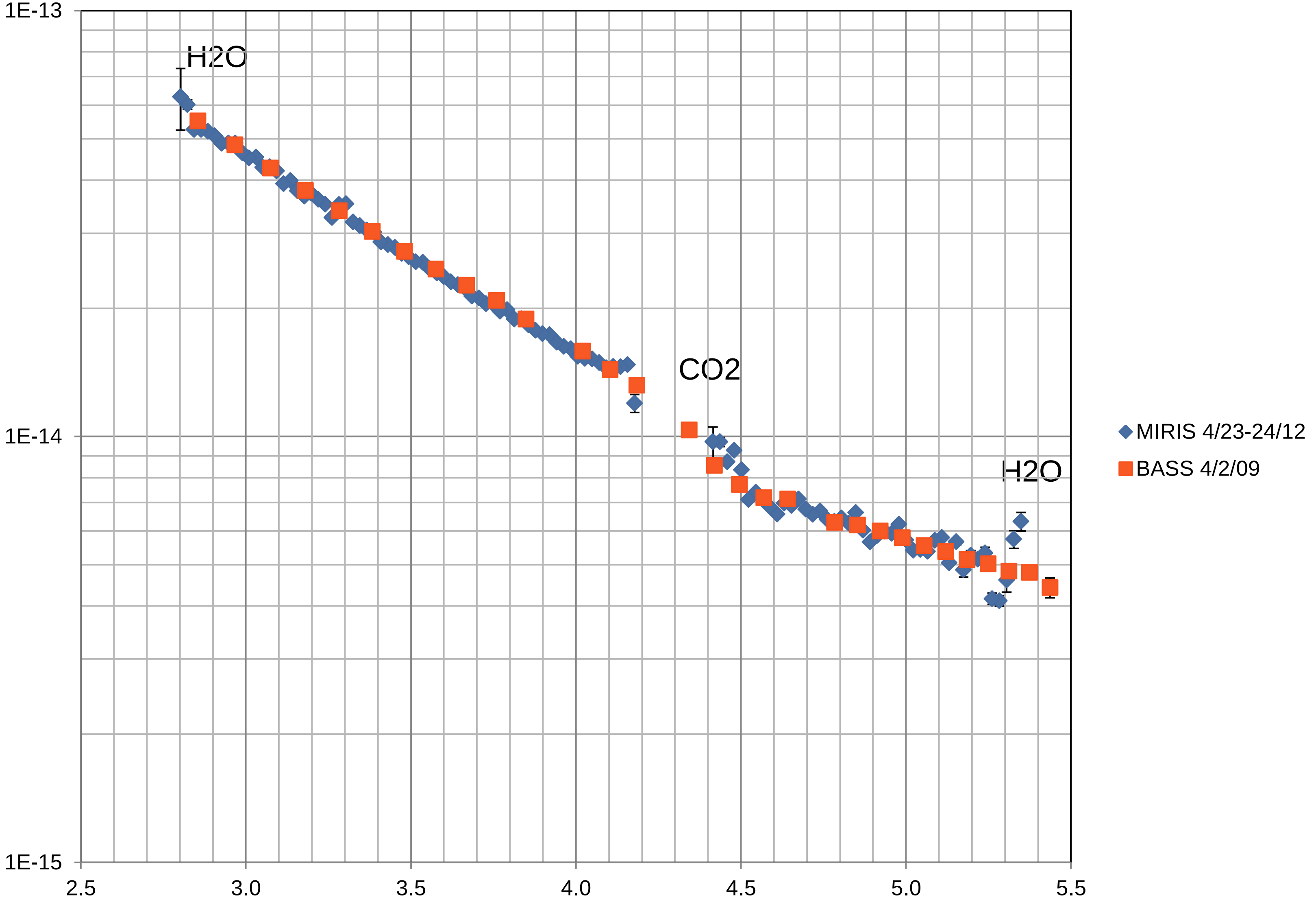
The Program

- Although the observing program started in 1993- 1994, a significant sensor (Broadband Array Spectrograph System -BASS) rebuild in 1995-1996 led to dramatically better performance
- Plan was, and is, to archive both ratios among many stars to a standard reference set and the resulting derived flux vs. wavelength
  - *Makes archive more valuable, as any improvement in the knowledge of the standard candle (a Lyr) and/or a CMa, can be retroactively applied to the database.*
- Originally spanned 3-13 um, now being extended shortward to 0.4 um
- Agreed to deliver to 8% absolute and relative accuracy specification
  - *Comparison with COBE data and on-orbit results for well-calibrated sensors on multiple programs support ~5% or maybe even a little better.*

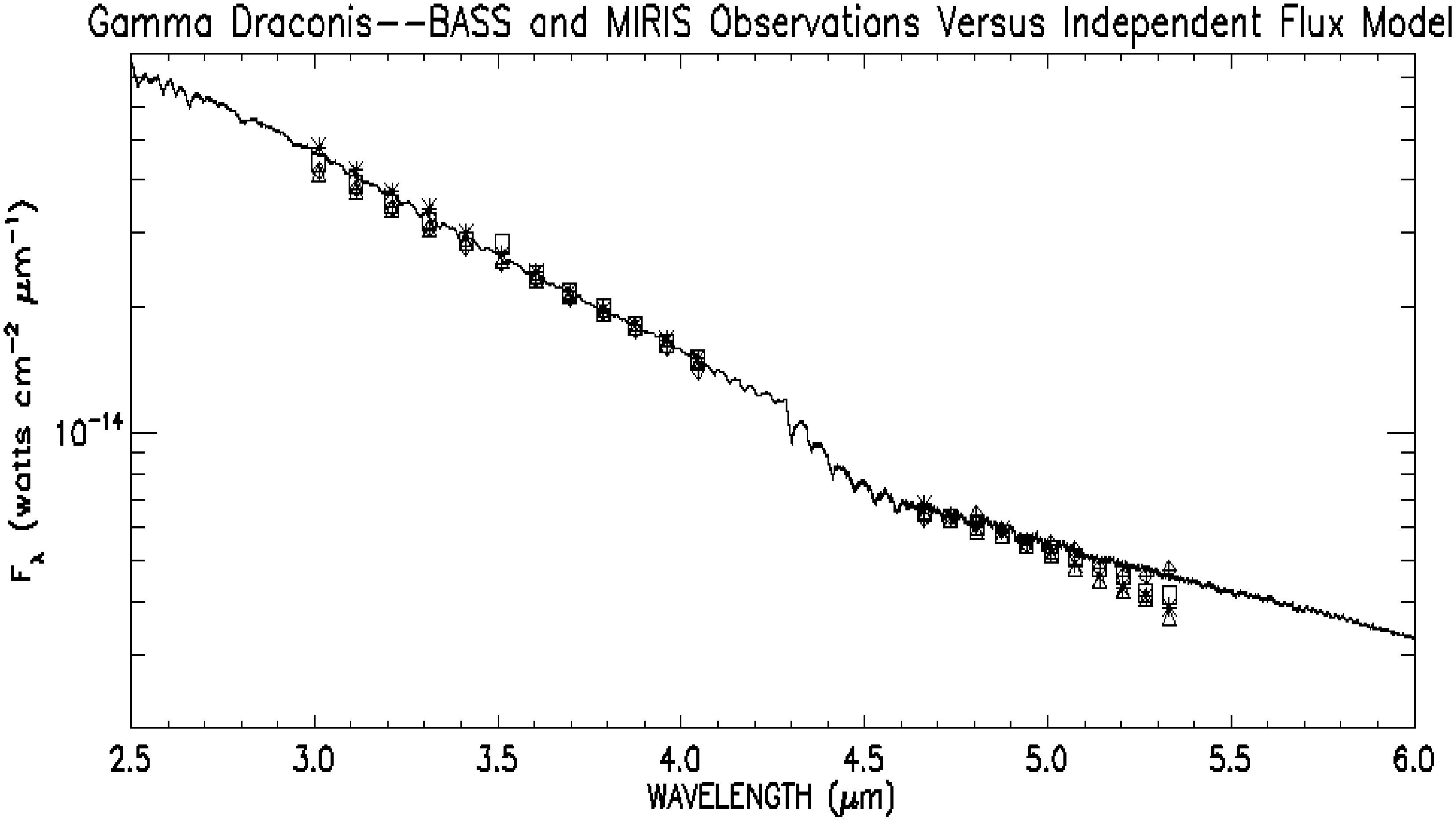
Current Status

- Uncertainty in the standard candle is now a significant uncertainty source, as repeatability and level of the observations are now routinely better than 5%, and often in the 1-3% range
- Comparisons among circular variable filter wheel (CVF) spectrometer, BASS, and the Aerospace Mid-wave InfraRed Imaging Spectrograph (MIRIS – operated by Rossano, Kim, and Owens) are now consistently better than 5%
  - *Recent comparison of independent data sets (Mt. Lemmon telescope and the MIRIS instrument compared to BASS on AEOS and IRTF telescopes) agree to better than 3% in level and shape*

Comparison of MIRIS data on gam Dra from April 2012 vs. a Boo with BASS data on gam Dra from April 2009 vs. a Lyr, with statistical errors on all points

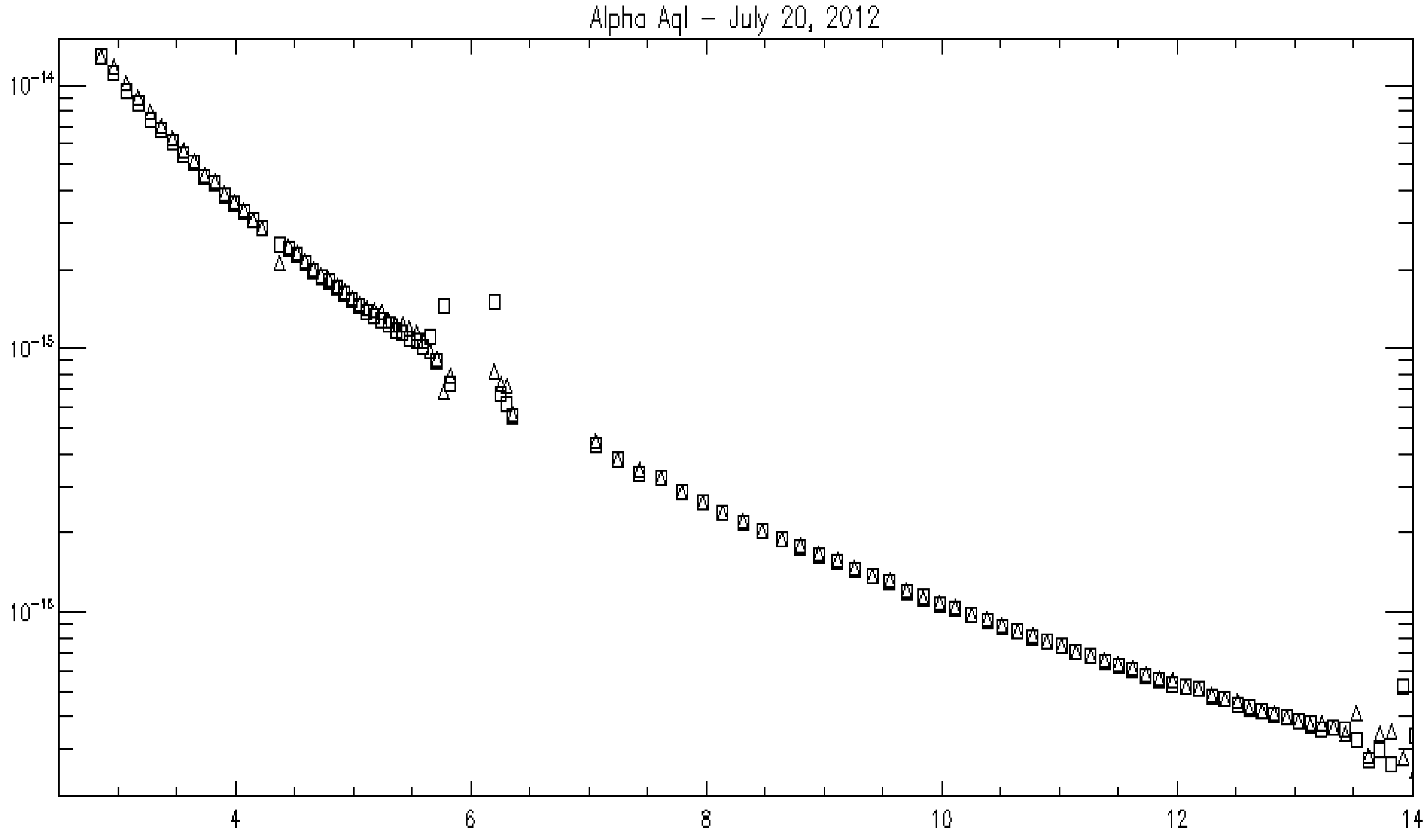


Overplot of MIRIS and BASS data on the Model for gamma Dra



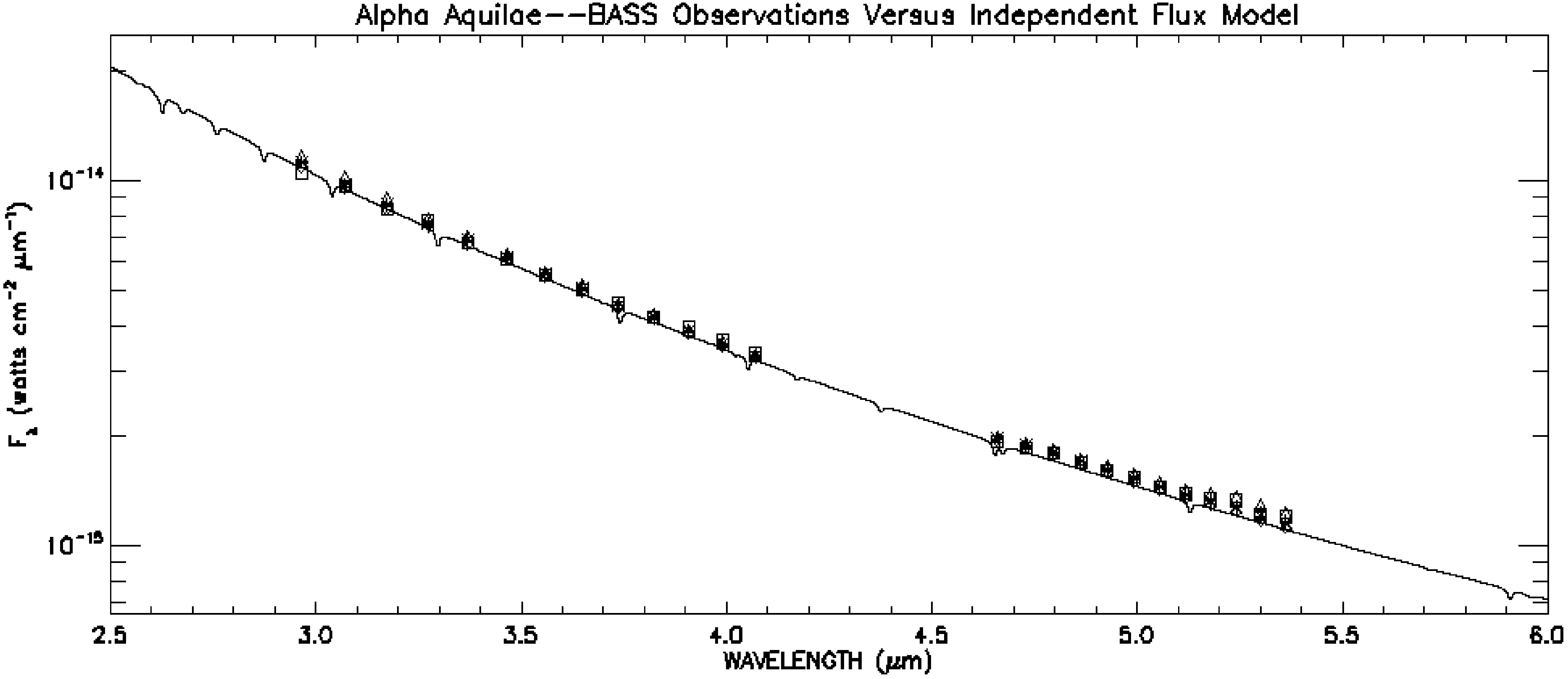
Alpha Aquila Spectra:
Comparison of 2 random, not the best, nights

triangles = July 24, 2012, squares = July 20, 2012

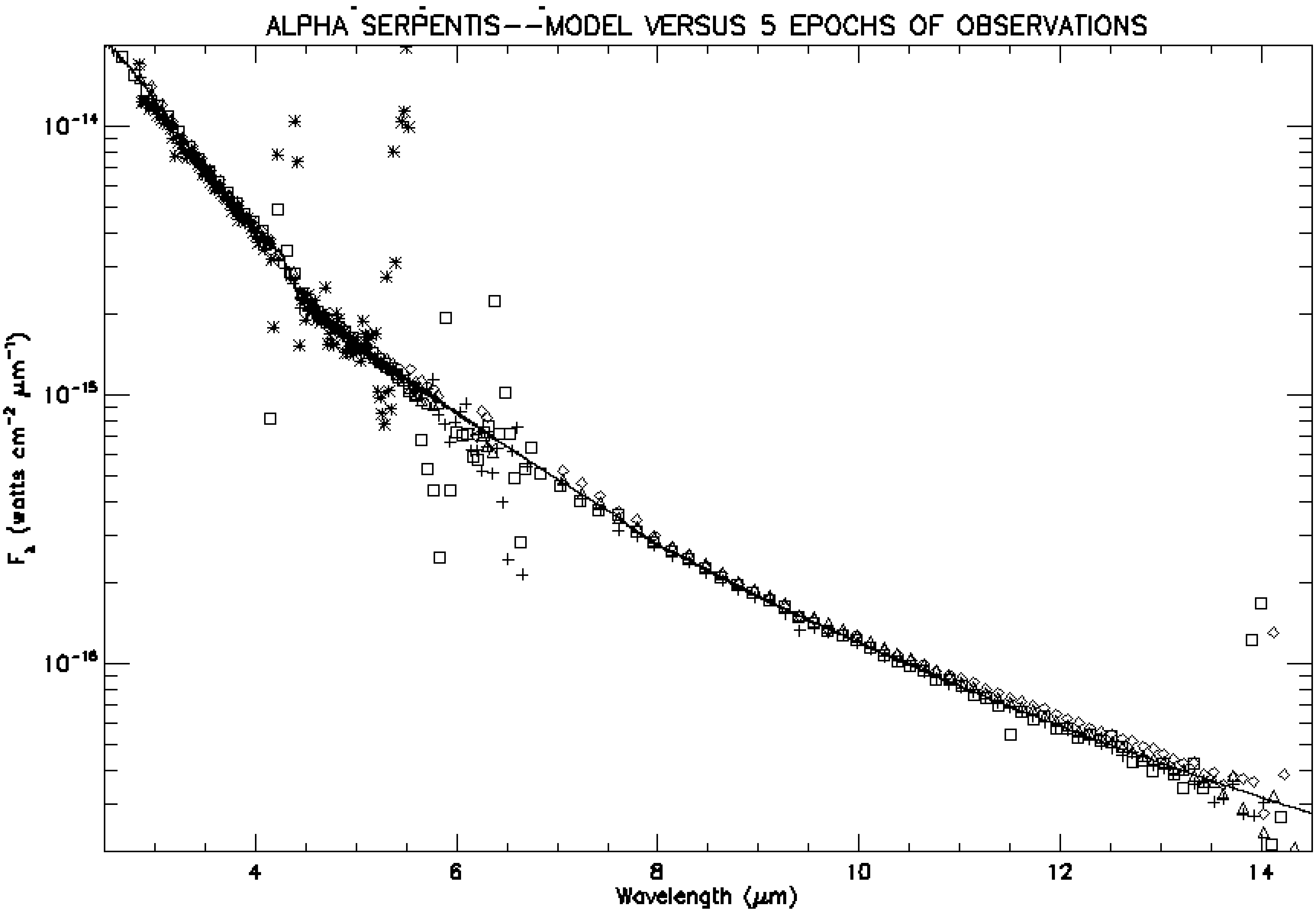


α Aql on all 5 nights in July 2012, with COBE-normalized Model, shows consistency of data, and a 4% shift in level since ~1990

(We will adjust the model for this difference)

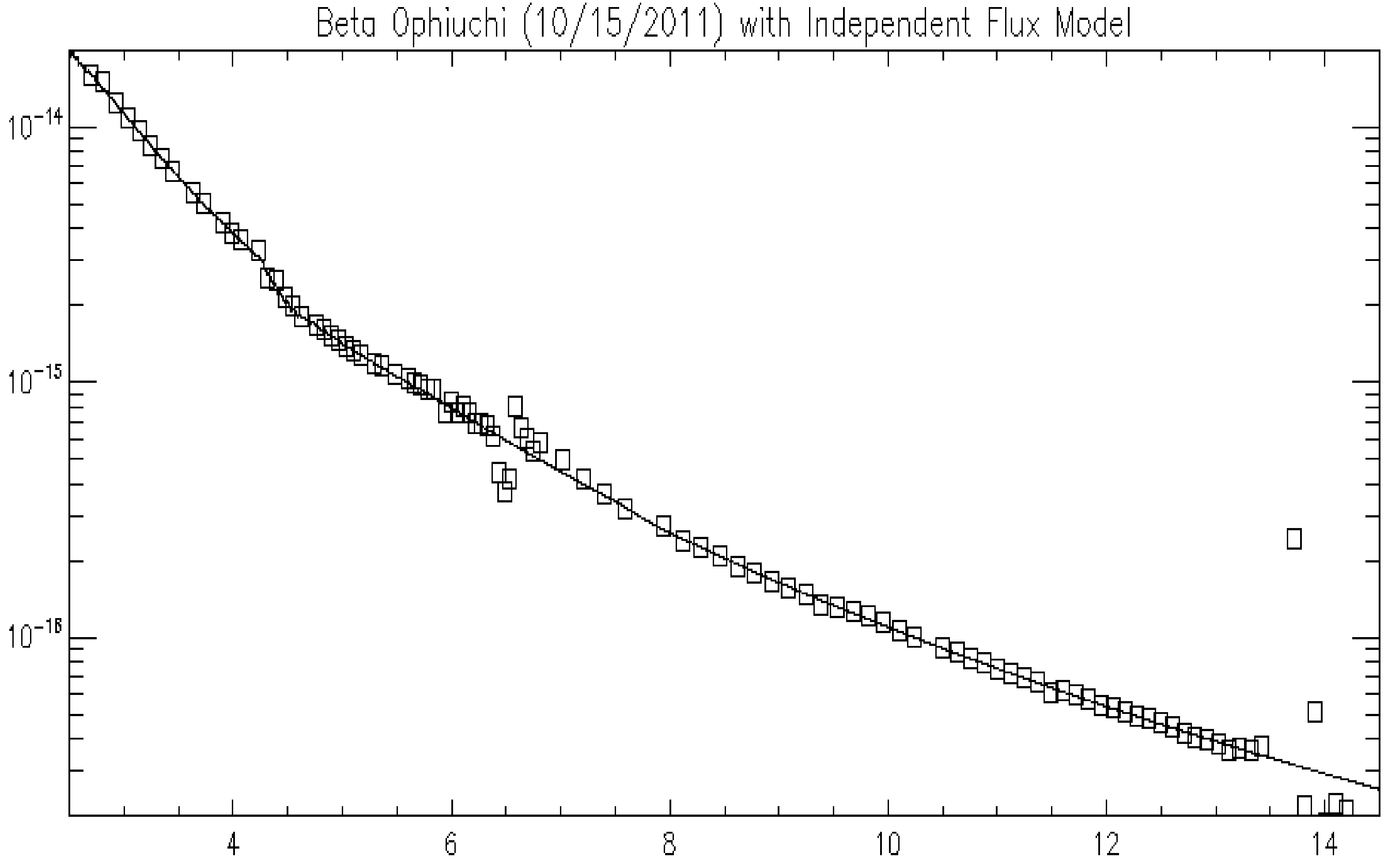


α Ser: 5 epochs compared to the Independent COBE/Model – 0.7% difference



β Oph compared to COBE model

- For stars with history of stability, new data and model often agree very well – e.g. β Oph

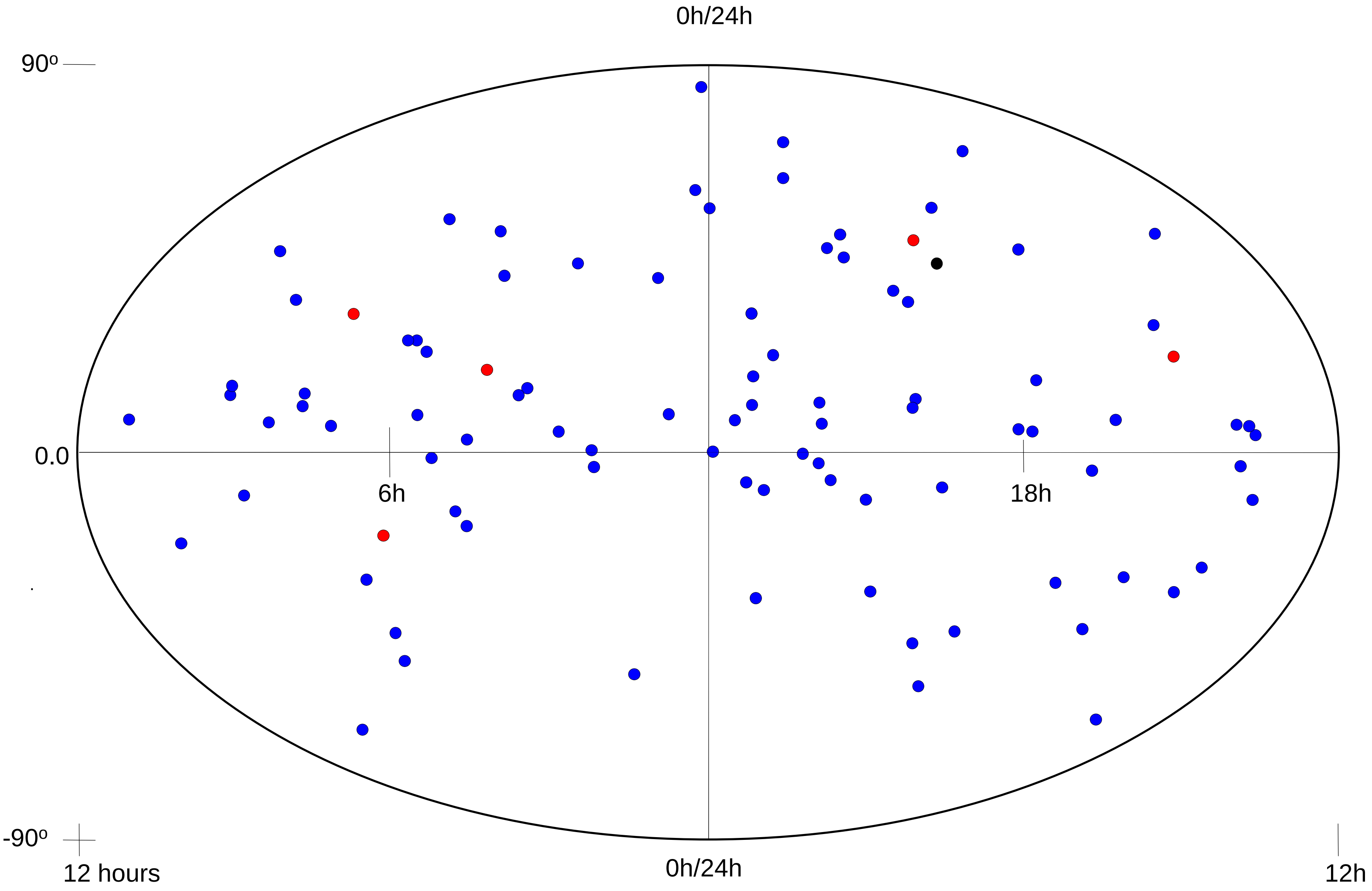


Recent Results

- In several instances the pre-launch calibrations (some tied to NIST) transferred to orbit and our data show agreement at the 5% or better level
  - *Combined with the comparison to COBE (0-4% agreement for stable stars), supports the claim that we know the absolute level and shape of the stellar energy distributions, and thus the targets, to 5% or better*
- More and more programs are using these datasets, providing a consistent calibration
  - *Supports data fusion with reduced ambiguity*
  - *Lends credibility to phenomena seen in the data, as differences are no longer due to differences in the assumed spectral energy distributions of the stars*
- In a couple of instances, data on stars whose calibration we provided showed changes in response of on-orbit assets which were then improved when corrective actions were taken
- One anomalous response was shown to be a mis-identified star
- One comparison between a model and sensor data that showed an out of family response was brought into agreement when data on that star were taken and used to correct the model

- Expanded to more than 90 stars currently being observed and trended (plus 5 reference standard stars with ~35 years of data showing their stability)

Distribution of Observed Stars on the Sky
5 reference standards in red



Recent Results – Extinction Coefficients

- Data are nominally reduced by taking observations on the reference standard at the same airmass and using a ratio technique
  - *One can't always get data on all objects and all reference standards at the same (<~0.1) airmass*
    - For coefficient as large as -0.1 at delta Airmass = 0.1, 1% effect
  - *Use one of two approaches*
    - Use observations of a single star over range of airmass and derive extinction coefficients – good when the atmosphere is stable, and this is an objective approach
    - Use Modtran calculations to adjust the amount of water, CO2, CH4, etc. in the atmosphere – good when weather fronts move over the observatory, for example, but a little more subjective
    - Comparisons between the two approaches have been made, and are generally in very good agreement
- Issue: Are the extinction coefficients for data taken at >2 airmasses, specifically in the 8-20 degree elevation range, different from those derived for higher elevation angles?
  - *Likely that this could be the case, due to:*
    - Seeing effects being larger at lower elevation angles
    - Optical depth effects being different for the long atmospheric paths at low elevation angles
    - Assumption of planar, uniform atmosphere breaks down close to the horizon

Bears on the procedural question of "Do we need standards at the larger airmasses, or can we use extinction coefficients at smaller values to extend calibration to larger airmasses?"

Reference Info: Extinction Coefficients

- We assume as a starting point, that the relationship between the signal, $S_{o\lambda}$, at a given wavelength, λ, that would be measured outside the earth's atmosphere, is related to the signal measured by the same instrument through some amount of airmass, X, by the equation:

$$S_{\lambda}(X) = S_{o\lambda}\, exp(\kappa_{\lambda} * X)$$

This defines the kappas, or extinction coefficients, as a function of wavelength, as the linear slope of the plot of ln(signal) as a function of airmass.

- Bemporad's data as tabulated by Schoenberg (1929) and reported by Hardie (1962) showed that this relationship held in the visible down to an elevation angle of 5 degrees or smaller, and Dr. John Williams (private communication, 1986), University of Denver, showed it worked down to at least as low an elevation angle as 5 degrees in the IR from an airborne platform in 1986, given the definition of the airmass, X:

- $X = \sec z - 0.0018167 (\sec z -1) - 0.002875 (\sec z -1)^2 - 0.0008083(\sec z -1)^3$

- Where sec z = secant (zenith angle) = cosecant (elevation angle)

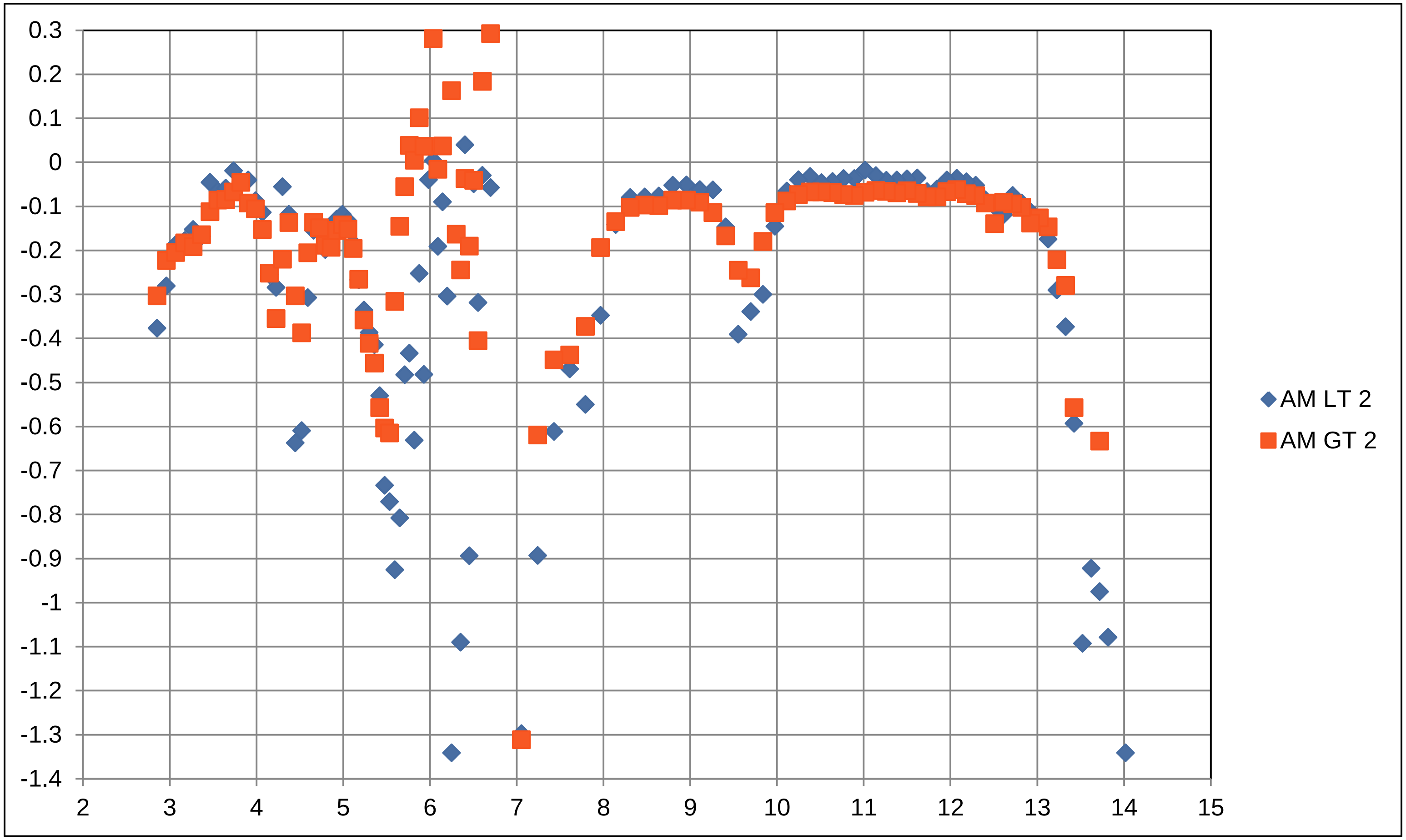
$$= (\sin \varphi * \sin \delta + \cos \varphi * \cos \delta * \cos h)^{-1}$$

φ = observer's latitude, δ and h are declination and hour angle of the source

Reference: Hardie, R. H., p. 184, in Astronomical Techniques, Stars and Stellar Systems, vol. II, ed. W. A. Hiltner, 1962

Examples of Extinction Coefficients

- K_λs derived for large airmass (>2, 6 AM values used here) are different, and larger, than K_λs for <2 AM (10 AM values used for this example)
  - *Requires multiple AM observations around AM used for unknown, or very small delta AM so corrections are still close*
- Believed due to addition of larger seeing component, besides larger optical depth with non-linear effects
- Requires more study, and we are working on this problem



Future Directions

- Expanded comparisons between MIRIS & BASS
- Aerospace is building a 1m facility at our home plant in El Segundo with plans to monitor variability of bright stars (too bright for astronomical sensors on > ~1.5 m telescope) to assess their value as an indicator of IR variability (which is usually less, if anything, than in the visible)
- Expand the observing program and comparison with theoretical models down to 0.4 microns

Summary

- The Aerospace stellar spectral energy calibration effort has matured, now covers >90 stars + 5 reference standard stars
  - *Observing techniques have been refined*
  - *Data reduction now undertaken with both extinction coefficients and Modtran model calculations – results agree very well*
  - *Wavelength coverage being extended to 0.4 -13 um*
  - *Looking at using visible data on smaller telescope (Aerospace 1 m) to monitor variability, as visible variability is expected to be a good indicator of IR variability*
- Results appear to be better than 5% in shape and absolute level
- The data are being applied across many programs, providing a uniform calibration reference and supporting higher fidelity data fusion and cross-program comparison of results
- We do respond to observing requests from existing and new programs

Acknowledgments: This work is supported at The Aerospace Corporation by the Independent Research and Development program. We gratefully acknowledge Trishana Prater's assistance with some of the data analysis tools.

Back-up/Reference

- List of stars observed to date, plus 5 reference standard stars and two sources used for wavelength calibration checks, follows.

The Aerospace Corporation Standard Star Program Integrated Observing List - IR ONLY

Aug-12

>90 stars!

Arranged by RA

	Star					
	T Cas	00 23 14.27073	+55 47 33.2067		M7.5e [K] = -0.780 HD1845	
224	delta Psc	**00 48 40.94433**	+07 35 06.2926		K4 IIIb [K]= 1.105	Double
337	beta And	**01 09 43.92388**	+35 37 14.0075		M0 III [K] = -1.846	Variable star
555	psi Phe	**01 53 38.74103**	-46 18 09.6048		M4 III [K] = -0.773	Semi-regular pulsating variable
681	omicron Cet	**02 19 20.792**	-02 58 39.50		M2-7 III	Mira Variable
689	69 Cet	**02 21 56.62767**	+00 23 44.4246		M2 III [K] = 1.050	
424	alpha UMi	**02 31 49.09456**	+89 15 50.7923		F7 Ib-II [V] = 2.005	Classical Cepheid (del Cep type)
911	alpha Cet	**03 02 16.77307**	+04 05 23.0596		M1.5 IIIa [K]= -1.823	Pulsating variable
921	rho Per	03 05 10.59385	+38 50 24.9943		M4 II [K] = -1.904	Semi-regular pulsating variable
	V1127 Tau	**03 43 18.10459**	+12 47 38.2070		M8 [K]= 1.066	Semi-reg pulsating variable
	IK Tau	03 53 28.87	+11 24 21.7		M6me [K] = -0.935	Mira variable
	CRL 618	**04 42 53.64**	+36 06 53.4		B0 d [K] = 8.807	V353 Aur (Post AGB star - proto PN)
1562	5 Ori	**04 53 22.77274**	+02 30 29.6104		M1 III [K]= 1.088	
1607	R Lep	04 59 36.34904	-14 48 22.5309		C7 [K] = +0.07	
1693	RX Lep	05 11 22.87154	-11 50 56.7222		M6.2 III [K] = -1.403	
1708	A Aur	05 16 41.35871	+45 59 52.7693		G8 III [K] = -1.74	
1903	eps Ori	**05 36 12.81335**	-01 12 06.9089		B0 Iab [K]= 2.273	Pulsating Variable
2061	alpha Ori	**05 55 10.30536**	+07 24 25.4304		M2 Iab [K]= -4.38	Semi-reg pulsating variable
2063	U Ori	05 55 49.16994	+20 10 30.6872		M6e -M9.5e [K]=-0.263	
	IRC+20139 .NE. eta Gem	**6:11:52**	**22:31:23.4 (or 42)**	1950		
2286	mu Gem	06 22 57.62686	+22 30 48.8979		M3 .0 IIIa [K]=-1.862	

2487	psi 06 Aur (57 Aur)	06 47 39.57703	+48 47 22.1222	K1 III [K]= 2.697	
2773	pi Pup	07 17 08.55678	-37 05 50.8962	K3 Ib [K]= -0.993	Semi-reg pulsating variable
	VY CMa	07 22 58.32877	-25 46 03.2355	M3/M4II [K]=0.291	
2878	sig Pup	07 29 13.83049	-43 18 05.1597	K5 III	Ellipsoidal variable
2854	gam CMi	07 28 09.79333	+08 55 31.9068	K3 III [K]= 0.993	
2943	alpha CMi	07 39 18.11950	+05 13 29.9552	F5 IV-V [K] = -0.658	Spectroscopic binary
3249	beta Cnc	08 16 30.92101	+09 11 07.9579	K4 III [K]= 0.190	Variable
3248	R Cnc	08 16 33.82789	+11 43 34.4557	M6e-M9e [K]=-0.705	
3482	eps Hya = 11 Hya	08 46 46.512	+06 25 07.69	G1 III [K] = 1.27	BY Dra variable
3547	zeta Hya	08 55 23.62614	+05 56 44.0354	G9 II-III [K] = 0.697	
3639	RS Cnc	09 10 38.79784	+30 57 47.2960	M6III [K]=-1.873	
3748	alpha Hya	09 27 35.24270	-08 39 30.9583	K3 II-III [K]= -1.127	Variable
3882	R Leo	09 47 33.48791	+11 25 43.6650	M6e-M8IIIe [H]=-1.755	
	CW Leo +10216	09 47 57.406	+13 16 43.56	C9, 5e [K]=1.19	
3950	pi Leo = 29 Leo	10 00 12.80589	+08 02 39.20	M2 III [K] = 0.49	Variable star
4069	mu Uma	10 22 19.73976	+41 29 58.2691	M0 III [K]= -1.009	
4210	eta Car	10 45 03.591	-59 41 04.26	WR [K]= 0.171	
	R Crt	11 00 33.85289	-18 19 29.58	M7 III [K]= -1.403	
4517	nu Vir	11 45 51.55957	+06 31 45.7413	M1 III [K]= 0.157	Semi-reg pulsating variable
4763	gam Cru	12 31 09.95961	-57 06 47.57	M3.5 III [J] = -1.994	
4846	Y CVn	12 45 07.82766	+45 26 24.9249	C5, 4J [K]= -0.738	
4902	psi Vir	12 54 21.16342	-09 32 20.3783	M3 III [K]= 0.165	Pulsating variable
4910	delta Vir	12 55 36.20861	+03 23 50.8932	M3 III [K]=-1.189	Variable
	RT Vir	13 02 37.98140	+05 11 08.3825	M8 III [K]= -1.060	
	SW Vir	13 14 04.38390	-02 48 25.1428	M7 III [H] = -1.606	
5015	sigma Vir	13 17 36.28327	+05 28 11.5221	M2 III [K]=0.473	

	5080	R Hya	13 29 42.78187	-23 16 52.7747	M6-9 [K]= -2.663	
		W Hya	13 49 01.99810	-28 22 03.4881	M7-9 [K] = -1.737	
		RX Boo	14 24 11.62662	+25 42 13.4091	M7.5 [K]= - 1.931	
	5589	RR UMi	14 57 35.00729	+65 55 56.8569	M5 III [K]= -.957	
	5603	sigma Lib	15 04 04.21608	-25 16 55.0606	M3/4 III [K] = -1.399	
	5705	phi01 Lup	15 21 48.36967	-36 15 40.9525	K5 III [K]= -0.153	Double
	5854	alpha Ser	15 44 16.07431	+06 25 32.2633	K2 IIIb [K]=0.15	Double
	6056	delta Oph	16 14 20.73853	-03 41 39.5612	M0.5 III [K]= -1.173	Variable
	6146	30 Her = g Her	16 28 38.54859	+41 52 54.0406	M6 III [H] = -1.850	
	6134	alpha Sco	16 29 24.45970	-26 25 55.2094	M3/M4 III [K] = -1.399	
	6406	alpha Her	17 14 38.85818	+14 23 25.2262	M5 Ib-II [V] = 3.06	
	6498	sig Oph	17 26 30.88004	+04 08 25.2940	K3 Iab [K]= 1.093	Variable
	6603	beta Oph	17 43 28.35265	+04 34 02.2955	K2 III [K]= 0.437	Variable
	6705	gam Dra	17 56 36.36988	+51 29 20.0242	K5 III [K] = -1.162	
	6832	eta Sgr	18 17 37.63505	-36 45 42.0667	M3.5 III [K] = -1.633	
	6905	zeta Tel	18 28 49.85980	-49 04 14.1122	K1 III-IV [K] = 1.814	
	7157	R Lyr	18 55 20.10223	+43 56 45.9315	M5 III [K] = -1.837	
	7259	beta CrA	19 10 01.756	-39 20 26.86	K0 II [K]=1.441	
		W Aql	19 15 23.347	-07 02 50.35	S [K]= -0.556	
	7525	gam Aql	19 46 15.58029	+10 36 47.7408	K3 II [K]= -0.720	
	7564	chi Cyg	19 50 33.92439	+32 54 50.6097	S62e-S104e [K] = -1.695	
	7557	alpha Aql	19 50 46.99855	+08 52 05.9563	A7 V [K]= 0.102	del Sct variable
		T Mic	20 27 55.18840	-28 15 39.8035	M7 III [K] = -1.650	
	7924	alpha Cyg	20 41 25.91514	+45 16 49.2197	A2 Iae [K] = 1.010	Pulsating Variable, Deneb
V1489 Cyg		NML Cyg 40448	20 46 25.54	+40 06 59.4	M6 III [K] = 0.791	
	7950	eps Aqr	20 47 40.55260	-09 29 44.7877	A1.5 V [K]= 3.737	Suspected Variable

8113	T Cep	21 09 31.78089	+68 29 27.2038		M5-9 [K] = -1.824	
8232	beta Aqr	21 31 33.53171	-05 34 16.2320		G0 Ib [K]= 1.212	Double
8289	7 Peg	21 42 15.45132	+05 40 48.4995		M2 III [K] = 0.973	Variable star
8316	mu Cep	21 43 30.46106	+58 46 48.1602		M2 Ia [K] = -1.620	
8308	eps Peg	21 44 11.15614	+09 52 30.0311		K2 Ib [K]= -0.86	Pulsating Variable
	EP Aqr	21 46 31.84756	-02 12 45.9306		M8 III [K] = -1.708	
8414	alpha Aqr	22 05 47.036	-00 19 11.46		G2 Ib [K]= 0.590	Double
8618	40 Peg	22 38 52.59013	+19 31 20.1532		G8 II [K]=3.768	
8698	lam Aqr	22 52 36.87441	-07 34 46.5542		M2 III [K]= -0.668	Pulsating Variable
8728	A Psa Fomalhaut	22 57 39.04625	-29 37 20.0533		A4 V [V] = 1.16	
8775	beta Peg	23 03 46.45746	+28 04 58.0336		M2.5IIe-IIIe [K]=-2.38	Pulsating Variable
8775	B Peg	23 03 46.45746	+28 04 58.0336		M2.5 II-IIIe [K]= -2.38	
8781	alpha Peg	23 04 45.65345	+15 12 18.9617		B9 III [K]= 2.647	Variable
8795	55 Peg	23 07 00.25965	+09 24 34.1703		M1 III [K]= 0.608	Variable
8834	phi (f) Aqr	23 14 19.35787	-06 02 56.3998		M2 III [K]= -0.099	
8916	tet Psc	23 27 58.09529	+06 22 44.3720		K1 III [K]= 1.859	
9037	XZ Psc	23 54 46.62421	+00 06 33.5186		M5 III [K] = 0.255	Pulsating variable
9066	R Cas	23 58 24.87336	+51 23 19.7011		M6e-M10e [K] = -1.404	

Special sources

	BD +303639	19 34 45.23224	+30 30 58.9435	WL cal	PN [K] = 8.108 Campbell's star, donut ~8" w/ central star
	NGC 7027	21 07 01.593	+42 14 10.18	WL cal	PN mV~10.9

Calibration reference standards

1457	a Tau	04 35 55.23907	+16 30 33.4885	Ref Std	K5 III [K] = -3.04
2491	a CMa	06 45 08.91728	-16 42 58.0171	Ref Std	A1 V [K]= -1.39
2990	b Gem	07 45 18.94987	+28 01 34.3160	Ref Std	K0 IIIb [K] = -0.936
5340	a Boo	14 15 39.67207	+19 10 56.6730	Ref Std	K1.5 III [K] = -2.91
7001	a Lyr	18 36 56.33635	+38 47 01.2802	Ref Std	A0 V [K] = 0.0 by our def, 0.13 from Simbad

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