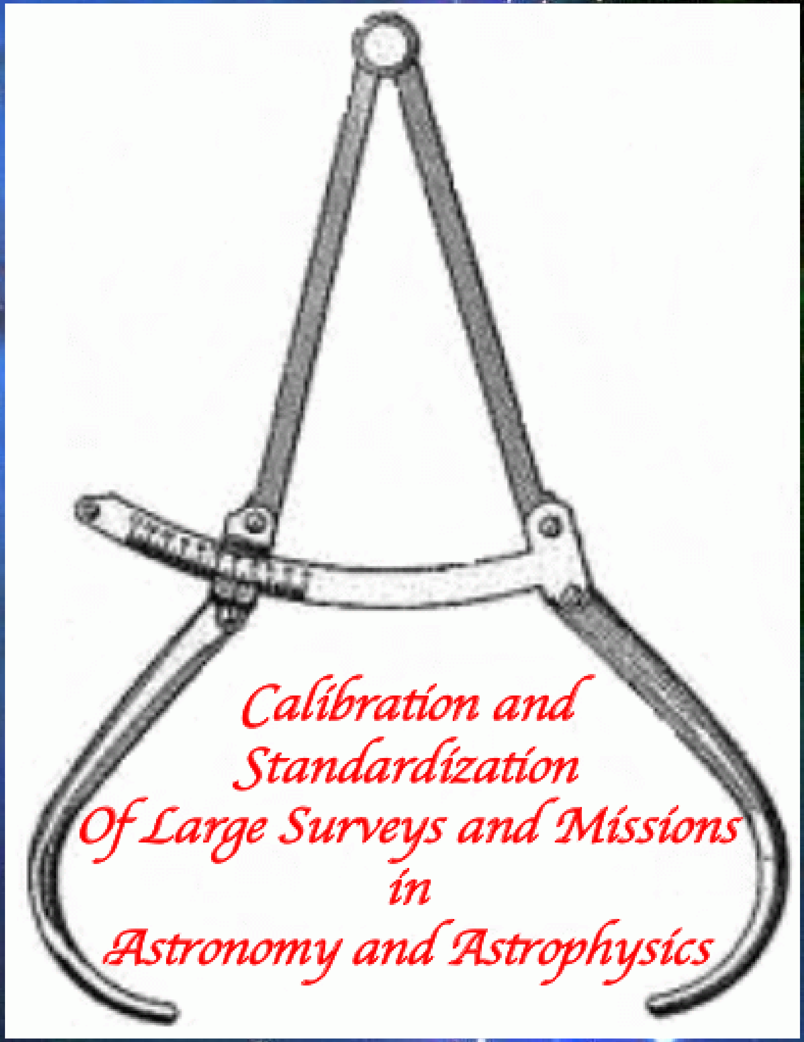
The Science Of Calibration

Stephen Kent, Fermilab
April 16, 2012



Why would anyone want to attend a meeting on CALIBRATION?

Outline

I. Hyperspace of All Data

II. Flavors of Calibration

III. Science Drivers

IV. Physics of Calibration

V. The Experimental Apparatus

VI. The Chain of Calibration

VII. Challenges for Missions and Surveys

VIII. Conclusions

I. Hyperspace of all Data

- **Four dimensions of electromagnetic radiation, Each characterized by r<u>ange</u> and p<u>recision</u>**
  - **Flux (e. g. erg/cm^2/s/hz) - usually at a specific frequency, wavelength, or energy**
    - **Range: 23 decades (Sun to faintest LSST objects)**
    - **Precision: 5 decades (Kepler 10 μmag)**
  - **Wavelength (both for flux and for velocity)**
    - **Range: 25 decades (3 khz - ISM to 100 TeV - CMB)**
    - **Precision: 10 decades (1 m/s for planet searches)**

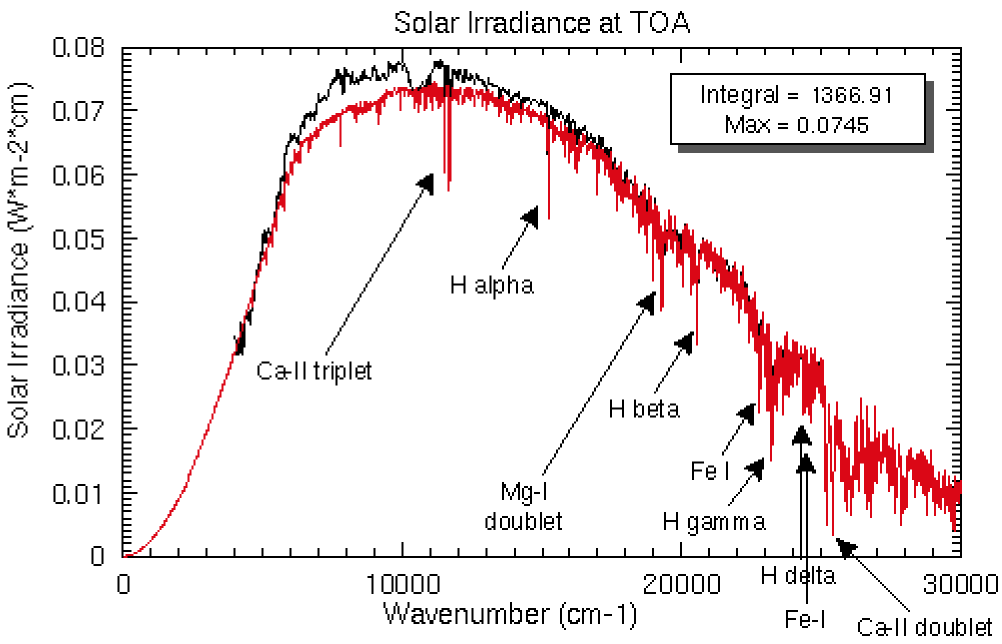
Hyperspace of all Data

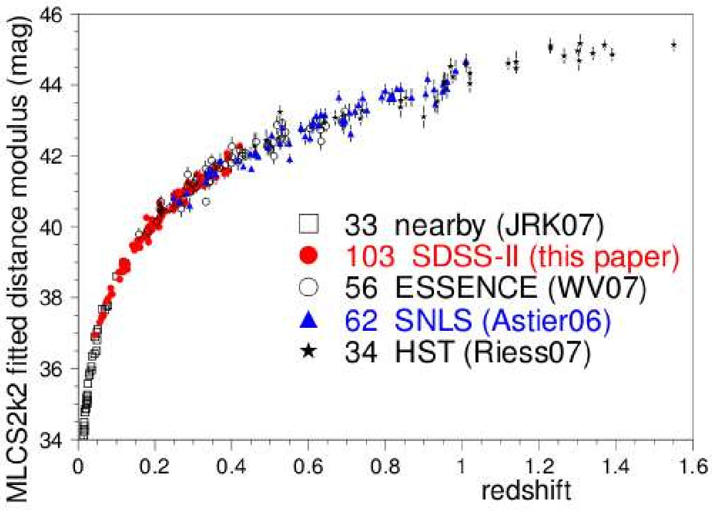
- Astrometry (2-d)
  - Precision - RA, Dec (10 decades - 24 µarcsec GAIA)
  - Angular rotation (11 decades from Earth to MW)
- Time:
  - Range: 18 decades (100 ns - pulsars to 6000 years - JD)
  - Precision: *(interferometers?)*

- **Extra dimensions**
  - 3 additional Stokes parameters
- **Extra particles**
  - Cosmic rays, neutrinos, axions, gravitons, neutralinos, ...

II. Flavors of Calibration

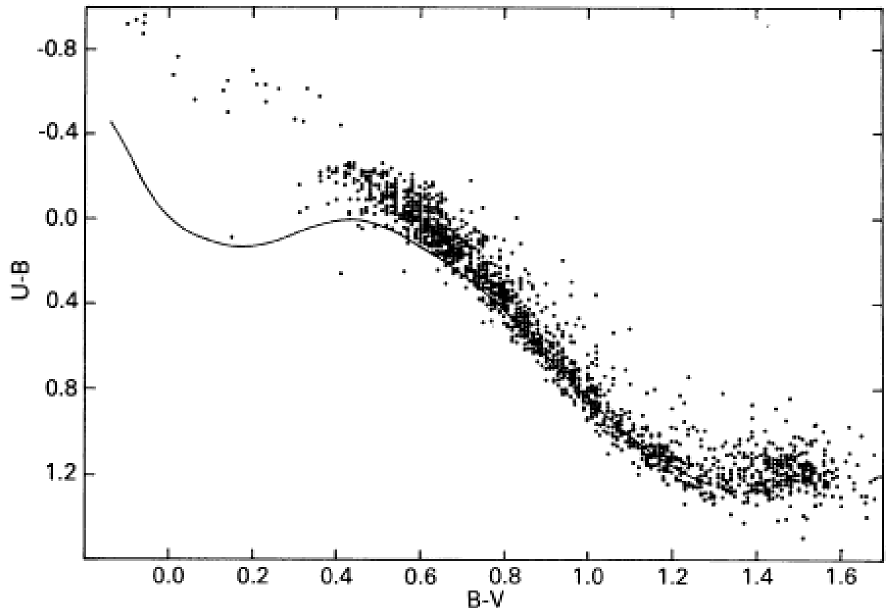
- **Absolute**
  - **E.G., fluxes in erg/cm^2/s/Hz**
  - **Sometimes we only care to within an arbitrary normalization**
    - **Flux - we don't know absolute distances or instrinsic luminosities of most objects**
    - **Time - we don't know absolute time since Big Bang**





Flavors of Calibration

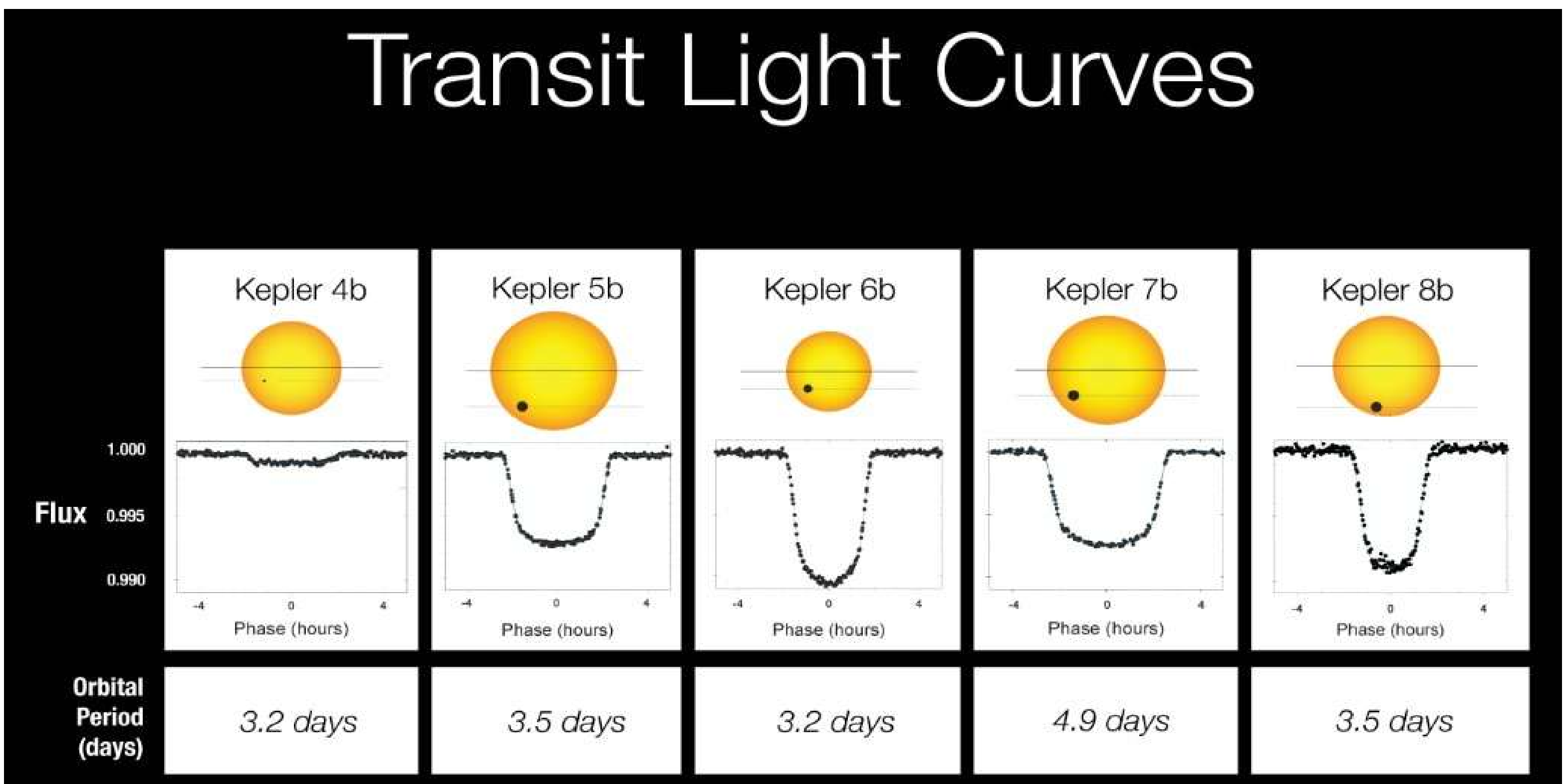
- Relative
  - “Intercalibration” - measurements from different instruments combined as if they were all made with one instrument; SI units, if needed are a separate step.



Halo subdwarfs with U-B excess (Sandage & Kowal)

Flavors of Calibration

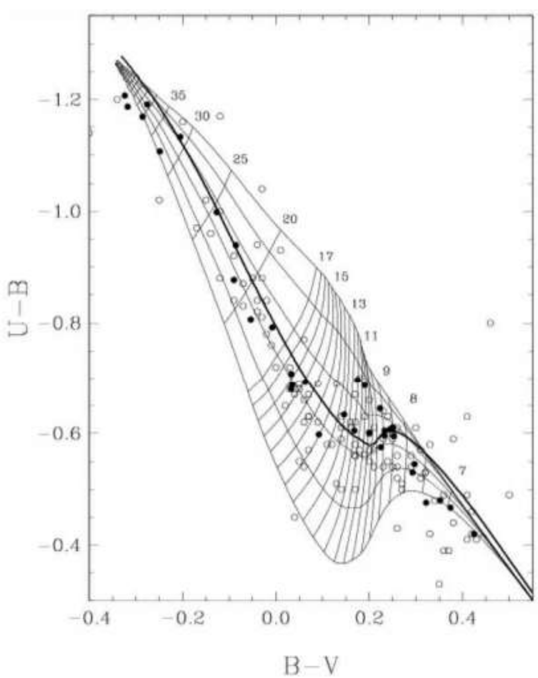
- **Differential**
  - **Precision measurements by a single instrument**
    - **Kepler (0.00001 mag accuracy)**

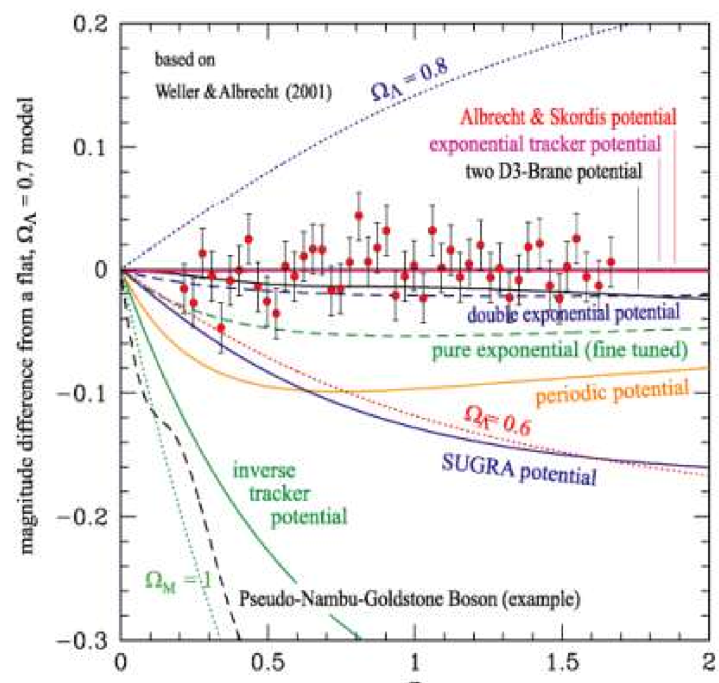


III. Science Drivers

Are we “science-limited” or “calibration-limited”?

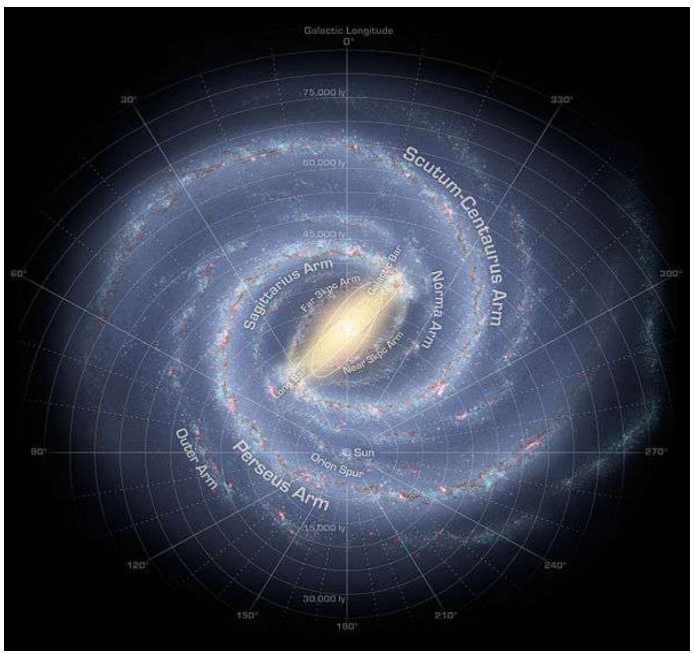
- **Absolute Calibration - flux**
  - **White Dwarf physics - soon to be limited by absolute flux calibration**
  - **Dark Energy from SNe - soon to be limited by relative flux calibration**

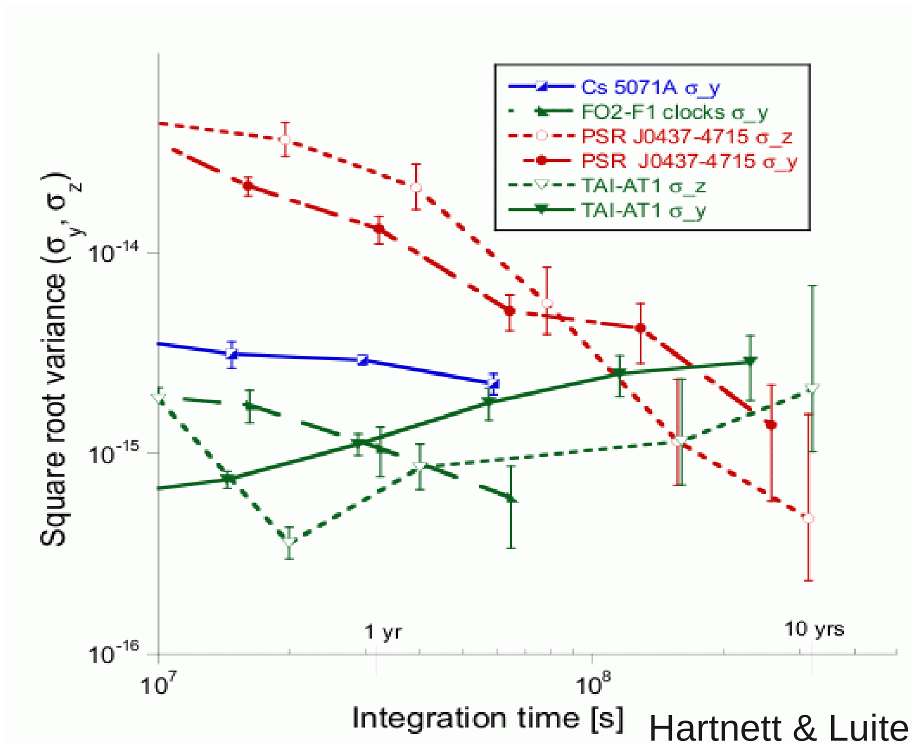




Science Drivers

- **Absolute Calibration - astrometry and time**
  - **Rotation of Milky Way - Limited by absolute astrometric calibration**
  - **Pulsars - close to limits of time calibration**



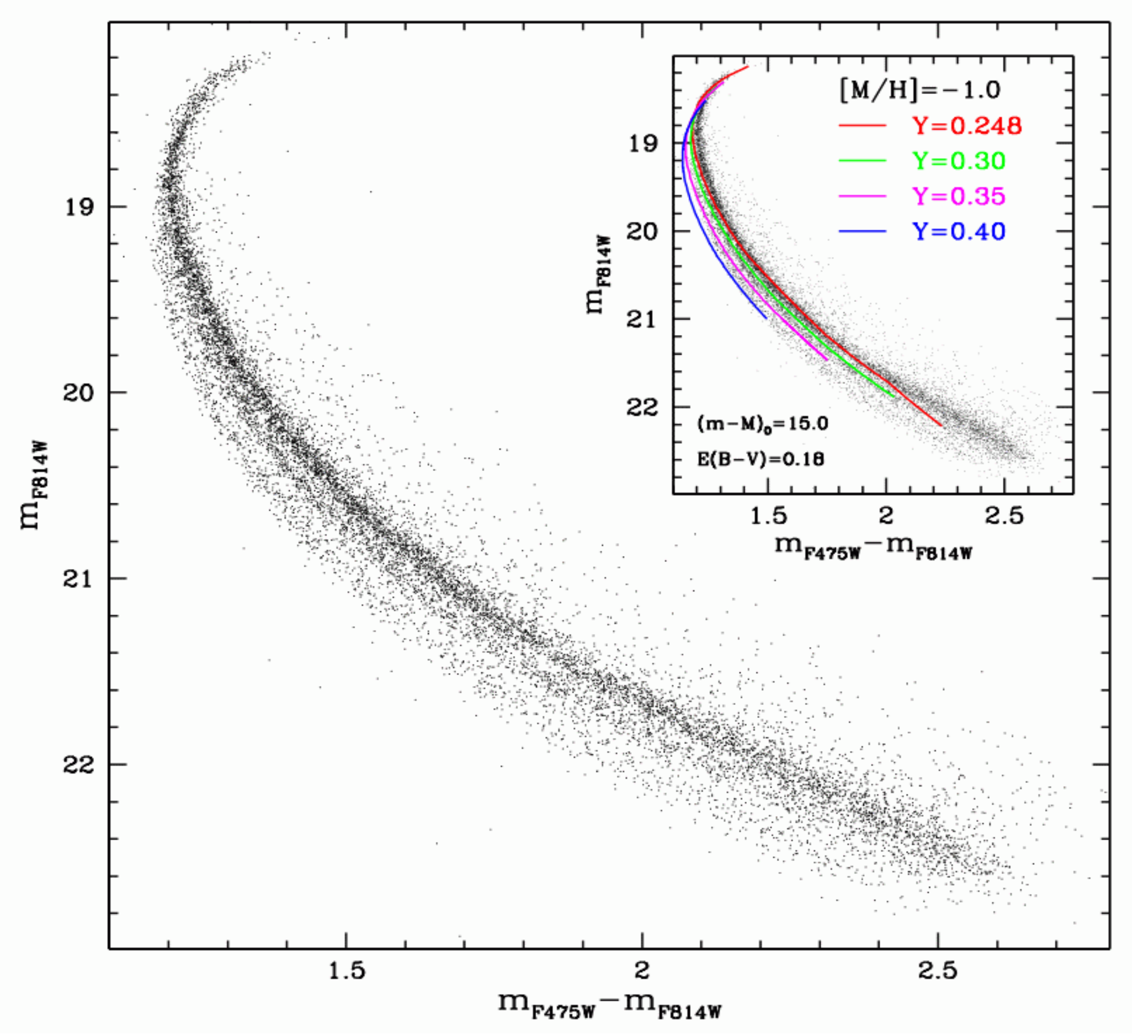


Hartnett & Luiten, arXiv:1004.0115

Science Drivers

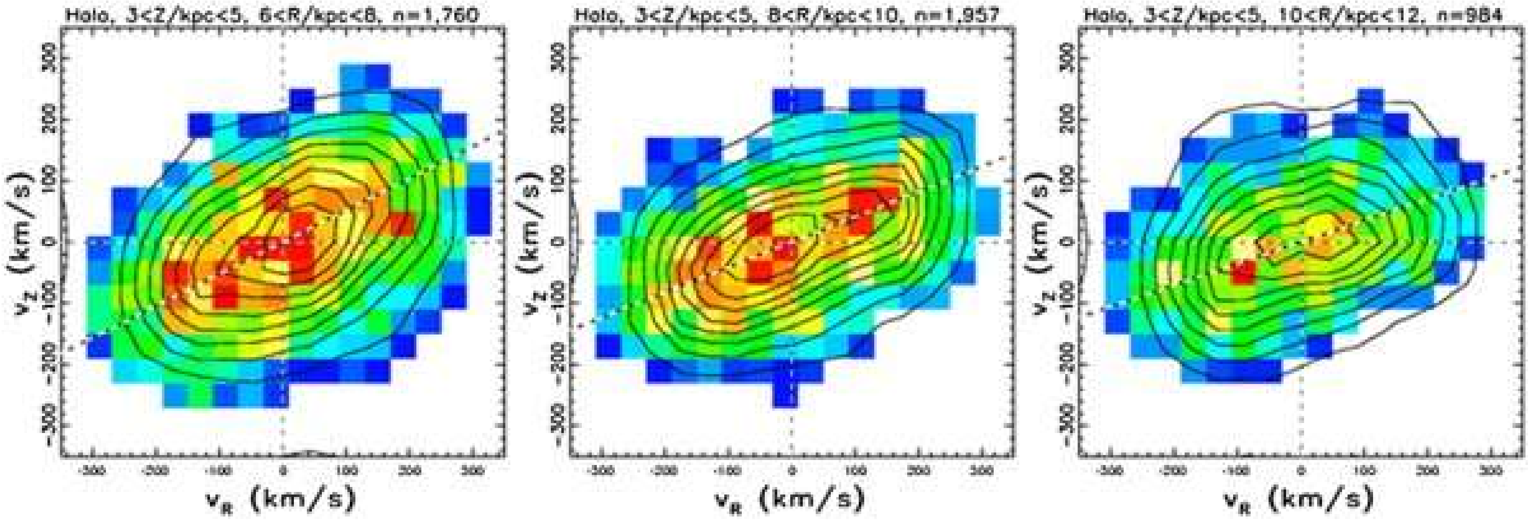
- **Relative Calibration - flux**

NGC 2808
Three main sequences!
(Piotto et al 2007)



Science Drivers

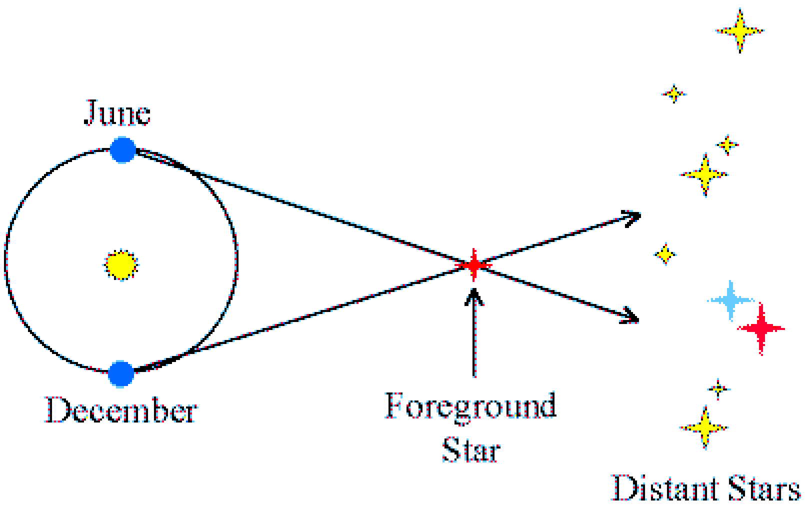
- **Relative Calibration - astrometry**
  - **Proper motions**

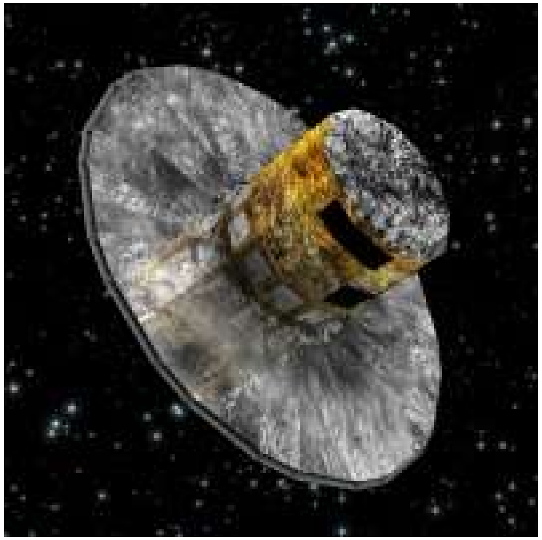


Tilt of velocity ellipsoid from radial velocities and proper motions of halo stars. (Bond et al. 2010)

Science Drivers

- **Differential Calibration - astrometry**
  - **GAIA - Parallaxes and distances of stars out to ~5 kpc**



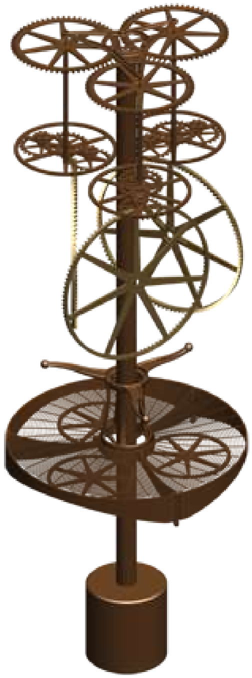


GAIA spacecraft

IV. The Physics of Calibration

Bring "physics" to the data

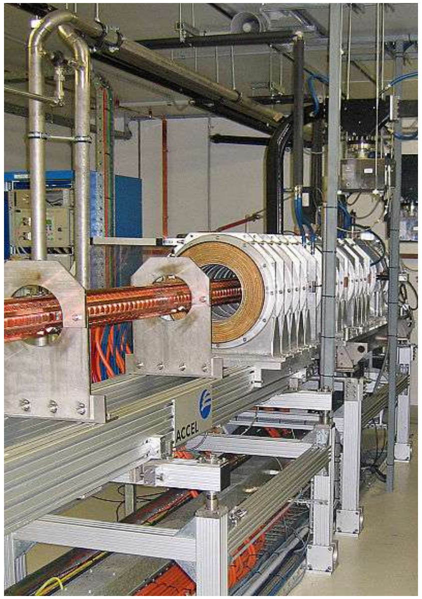
- Time
  - 10,000 year clock
  - Atomic clocks
  - GPS (but see Opera experiment)



USNO

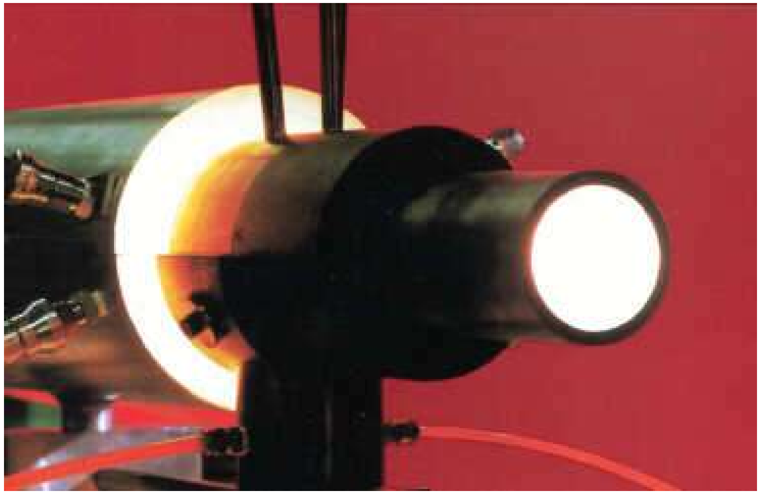
The Physics of Calibration

- **Wavelength - depends on domain**
  - **Radio - frequency synthesizer**
  - **Optical - emission-line lamps, filters, monochromators**
  - **X-ray; gamma ray - accelerator technology (voltage)**



The Physics of Calibration

- Flux - depends on domain
  - Black bodies (radio to optical) - Temperature
  - Synchrotron - voltage and curvature radius
  - Test Beams - Bremsstrahlung
  - Calorimeters - NIST LOCR



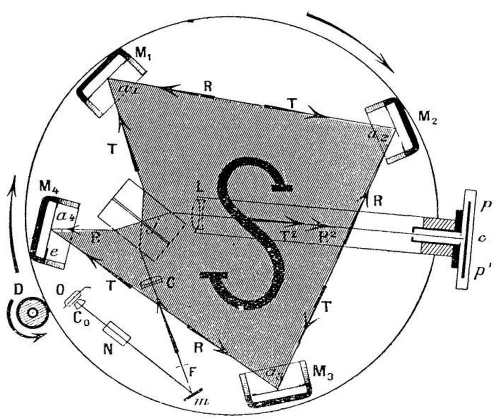
Thermo-Gauge BB furnace

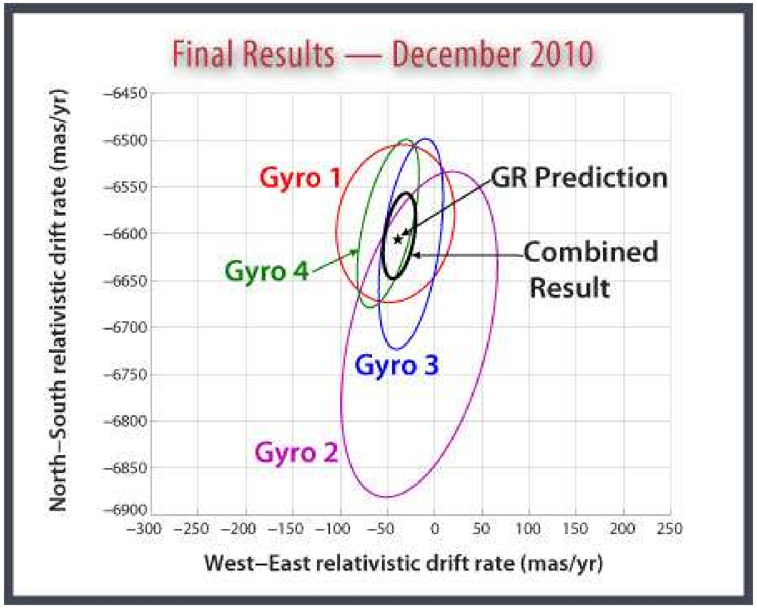
Precision thermometer

NIST SURF III

The Physics of Calibration

- **Astrometry - Radian - no SI units, but we still want an absolute inertial frame**
  - **Milky Way rotates at 5 mas/yr**
  - **Sagnac Interferometers (10^5 mas/yr)**
  - **Gravity Probe B (7 mas/yr)**
  - **Use Mach's Principle (ICRS)**





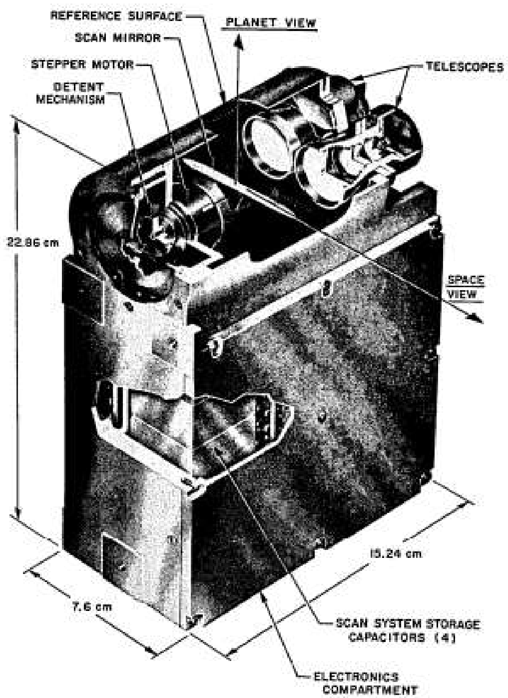
V. The Experimental Apparatus

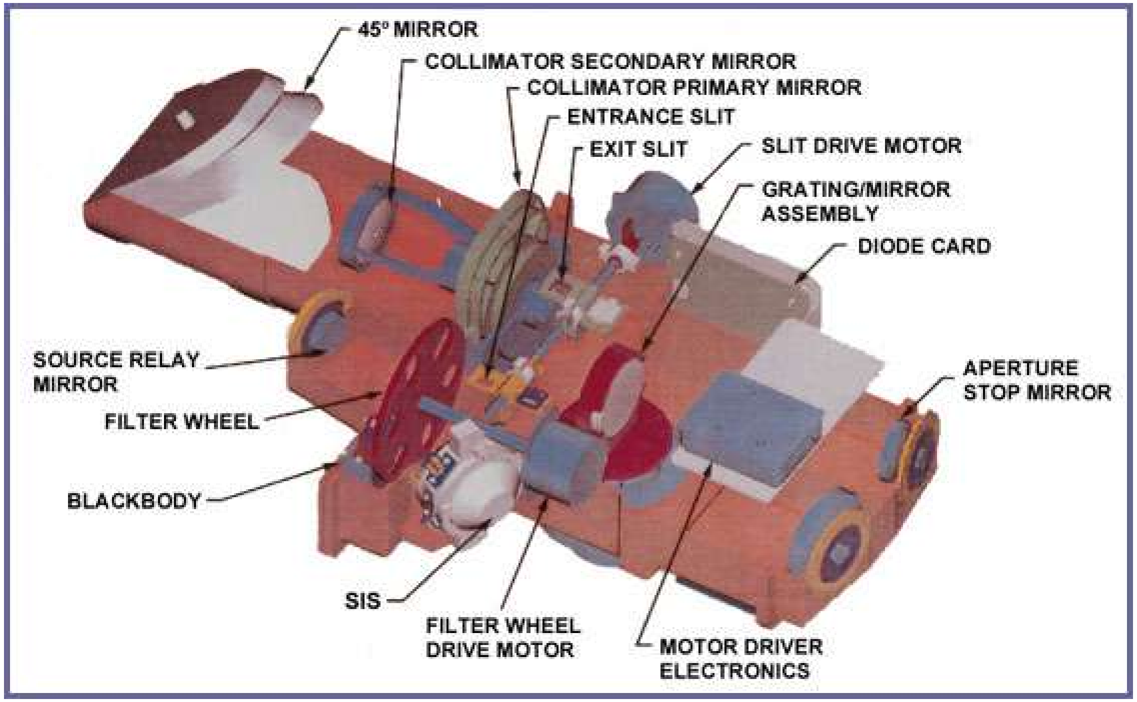
- The three components
  - Detector/Instrument
  - Telescope
  - Atmosphere
- Ideal world - observe our physics source the way we observe our object. Reality ...
  - Calibrate detector/instrument, telescope, atmosphere either individually or in different combinations

V. The Experimental Apparatus

Detector / Instrument

- **Radiometers**
  - Chop between source and thermal load





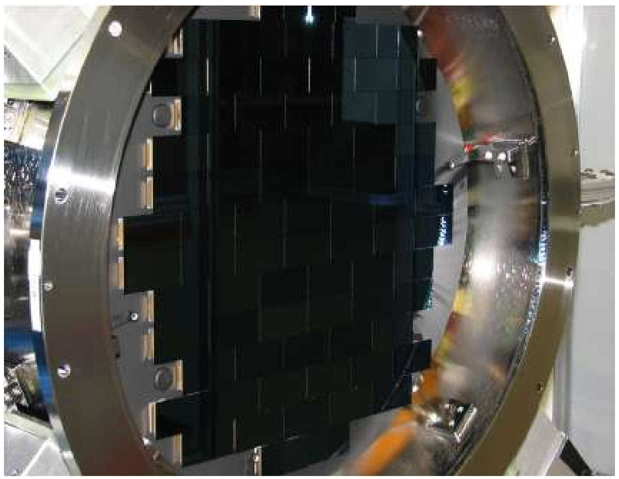
Mariner 6/7 radiometer (Mars Calibration) (Chase 1969)

MODIS (Earth Sensing Calib.)

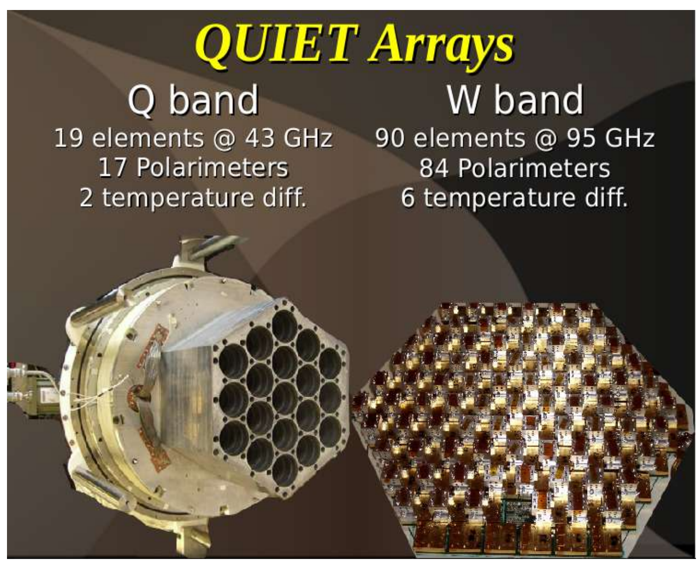
V. The Experimental Apparatus

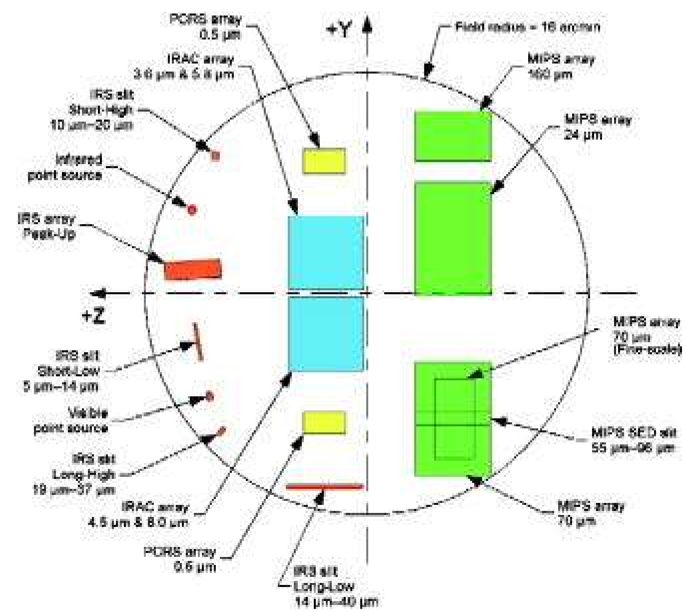
Detector / Instrument

- **Mosaic Arrays - Flatfielding**



DES - DECam





Spitzer Focal Plane

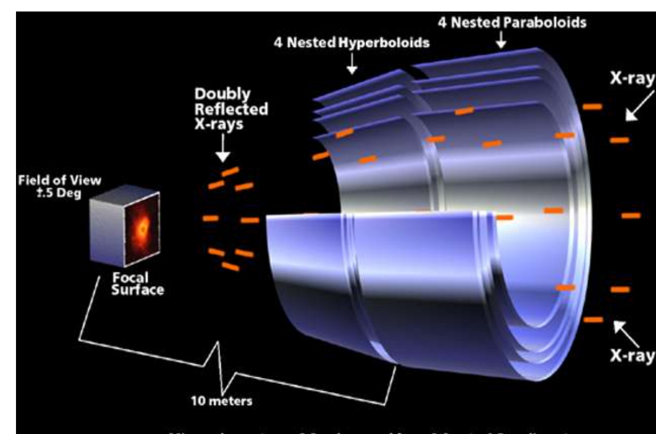
The Experimental Apparatus

Telescope

- Radio - 1st principles to calculate gain
- Optical/X-ray - Calibrate telescope + instrument + detector as a single system
  - Flux and wavelength calibrations intermingled
  - No “source at infinity”

Calibrated Radio Horn

Optical (SDSS)

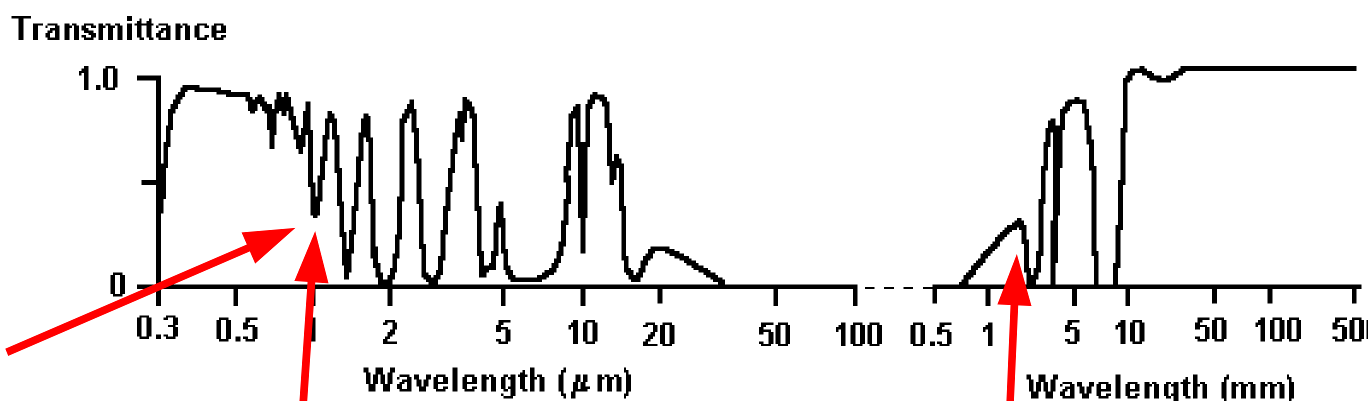


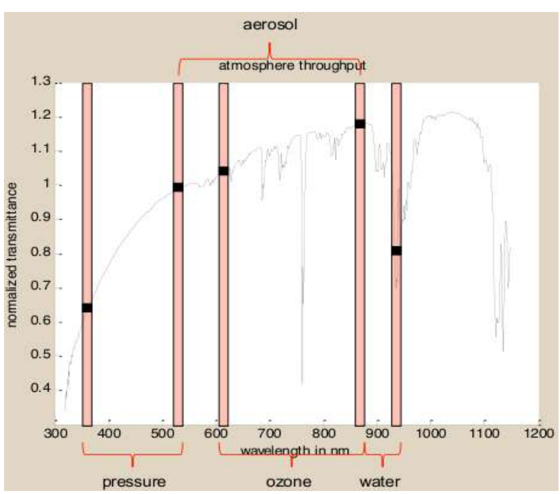
X-ray (Chandra)

The Experimental Apparatus

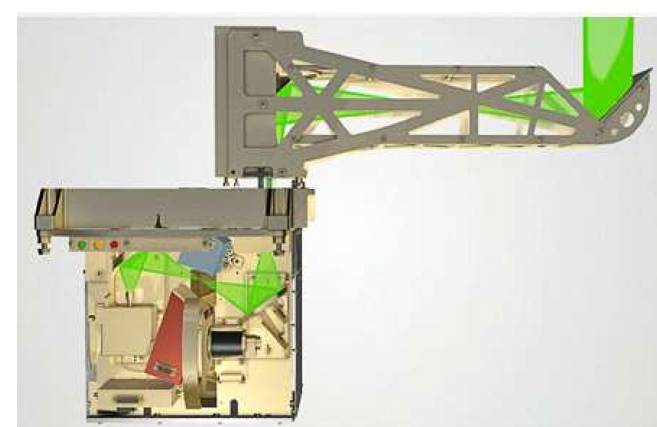
Atmosphere

- "Water, water everywhere, nor any drop to drink." Time-variable. Affects:
  - opacity
  - bandpass
  - timing





AtmCam



ALMA WVR

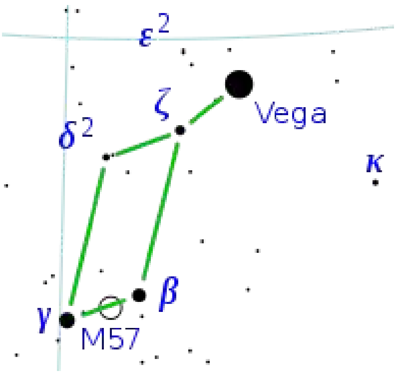
VI. The "chain of calibration"

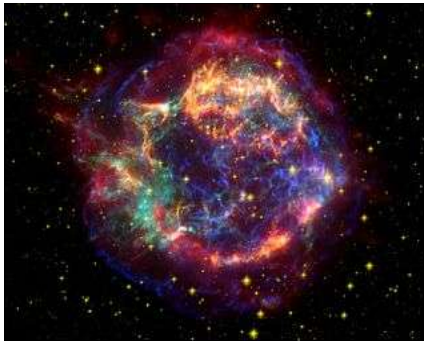
When you can't bring physics to the data

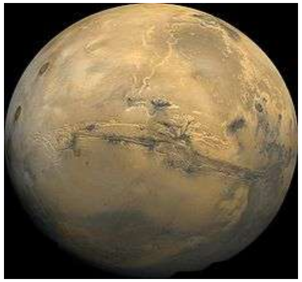
Calibration is a chain of ratios

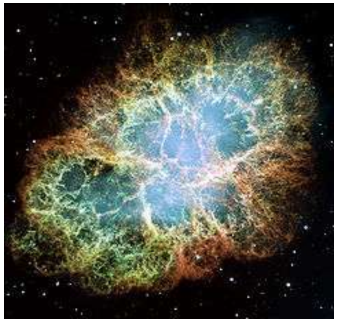
Answer = (Data/A) * (A/B) * (B/C) * (C/D) ... * (physics ref.)

- **Fundamental flux standards**
  - Cass A
  - Mars
  - Alpha Lyra
  - HST White Dwarfs
  - Crab Nebula
- **The standard star network**
  - Absolute
  - Relative



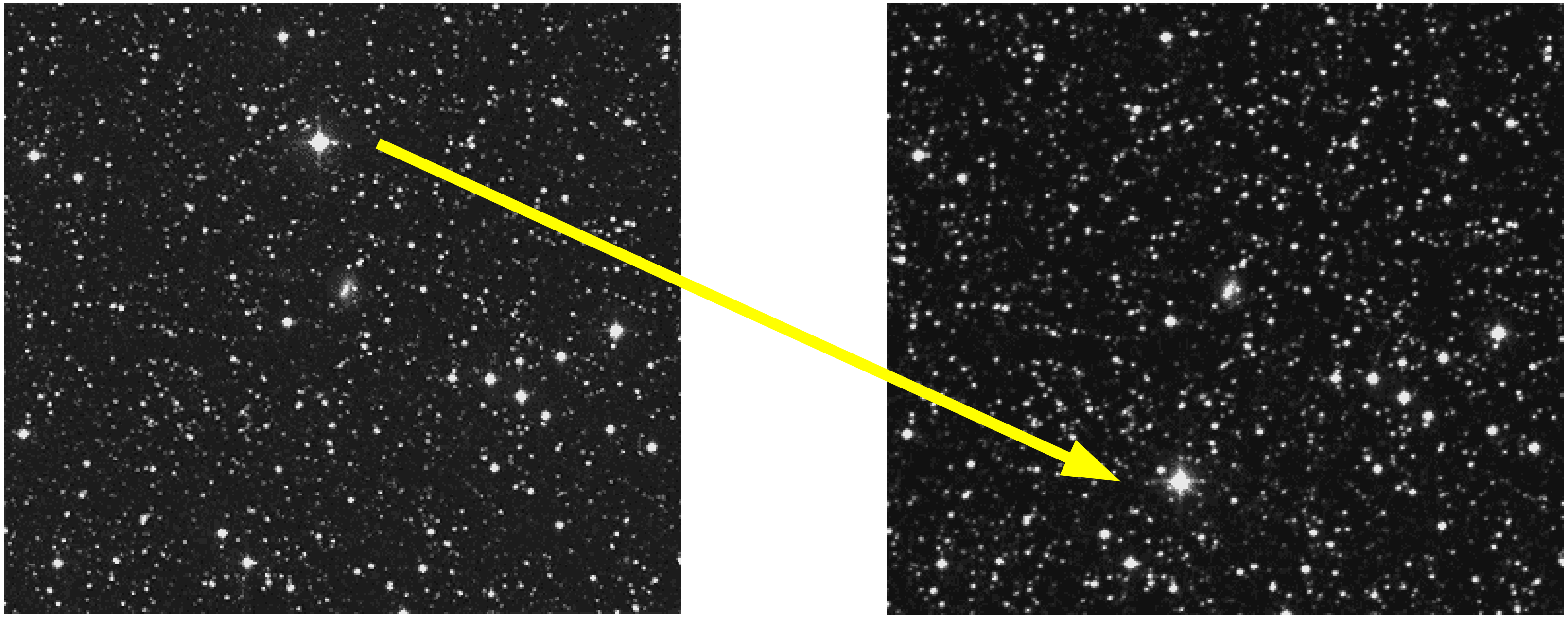






The “chain of calibration”

- Astrometric standards
  - ICRS
  - NOMAD transfer standards
    - Limited by proper motions



The "chain of calibration"

- **Error Creep**
  - **COBE carried 1 mK thermometers, but final result was accurate to 5 mK**
- **Cure for Error Creep**
  - **Use multiple, parallel methods for each link of the chain.**

MSX
3 legs of calibration
(Burdick et al. 1996)

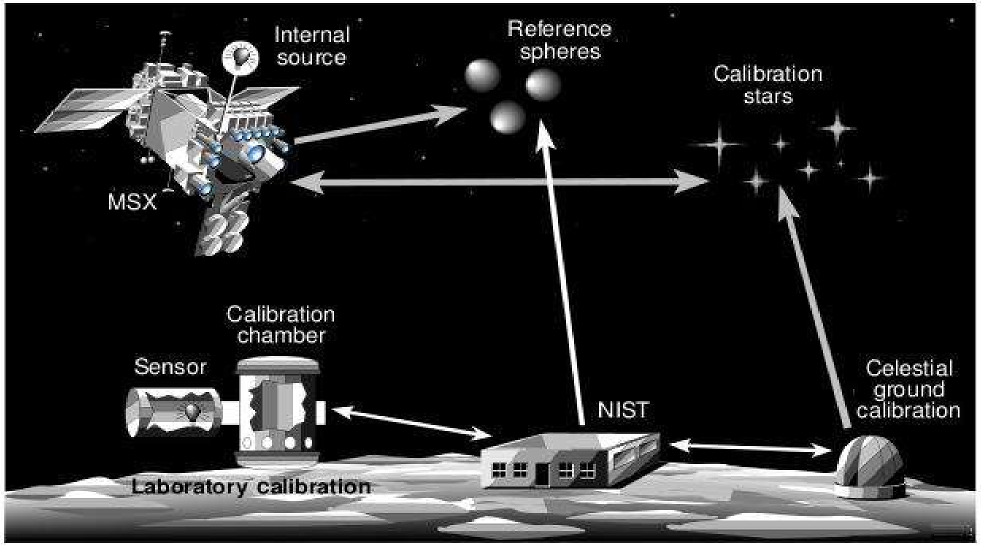


Figure 3. NIST-traceable MSX calibration process.

VII. Challenges for Large Surveys and Missions

- Space Missions
  - Good news - we eliminate the atmosphere (astronomer)
  - Bad news - we introduce the atmosphere (earth scientist)
  - Ugly news - calibration hardware costs $$$
  - You may not know what you need to calibrate until after launch
  - How can you assure that you will meet calibration requirements?

Challenges for Large Surveys and Missions

- **Array detectors now appearing in microwave applications (e.g., QUIET, SPT) - flatfielding techniques from optical now needed in a new domain.**
- **Even in optical larger FOV mean that techniques that work for single detectors don't work for large arrays (ghosting, spatially varying sky intensity)**

Challenges for Large Surveys and Missions

- **Requirements are more demanding than in the past**
  - **LSST wants 1% accuracy per observation; in the past we achieved this with repeat observations**
- **Radio - we are going to higher frequencies**
  - **Traditional flux calibrators too weak.**
- **Need new, all-sky (North & South) network of astrometric, flux standards to fainter limits**

Challenges for Large Surveys and Missions

- For a survey, it's not “what is the best that I can do” but rather “what is the worst that I will consider acceptable?”
- How do we report data? Bandpass varies across FOV. Traditional methods of using color terms no longer adequate as we include objects with non-smooth spectra (emission lines) and want <1% accuracy.

Run 5935 Col 2 Field 109

VIII. Conclusions

- For many problems in astrophysics, we are “calibration-limited,” not “science-limited.”
- The “space” of astronomy data is large, and while our calibration needs might seem disjoint from one another, there is actually considerable commonality.