Astronomy 192
Principles of Astronomical Measurement

This course is intended to provide an overview of astronomical measurements, with treatments of fields from high energy astrophysics to radio astronomy. We'll begin with a philosophical overview and a review of astronomical observables, units and definitions, followed by an introduction to Signal-to-Noise. The remainder of the course is split into four sections, the first on telescopes and external signal degradation (what goes wrong with your signal before it's even detected), the second on detectors and detector physics, the third on instrumentation (spectroscopy, broad band measurements, interferometry polarimetry) and the last on experimental statistics (parameter estimation and hypothesis testing).

Prerequisites: Mathematics at the level of advanced calculus, facility with computers, physics at the level of introductory quantum mechanics and atomic physics. (Physics 15 abc, Applied Math 105 or equivalent)

Texts: (to be used sparingly!) -

Rieke, G. *Detection of Light from the Ultraviolet to the Submillimeter* **(Cambridge: Cambridge) ISBN 0 521 41028 2.**

Bevington, P. 1992, *Data reduction and Error Analysis for the Physical Sciences* **(New York: McGraw Hill) ISBN 0-07-911243-9.**

also recommended:

Lyons, L. 1986, *Statistics for Nuclear and Particle Physicists*, **(Cambridge: Cambridge) ISBN 0 521 37934 2.**

Mclean, I. 1997, *Electronic Imaging in Astronomy*, **(New York: Wiley) ISBN0 471 96972 9 (paper), 0 471 96971 0 (hard).**

Other Books of Interest:

* **Allen -** *Astrophysical Quantities*

Born and Wolf - *Principles of Optics*

Rolfs and Wilson - *Tools of Radio Asronomy*

* **Dereniak and Crowe -** *Optical Radiation Detectors*

Gray - *Observation and Analysis of Stellar Photospheres*

Hillier - *Gamma Ray Astronomy*

Kitchin - *Astrophysical Techniques*

Lupton — *Statistics in Theory and Practice*

* **Schroeder -** *Astronomical Optics*

* **Taylor -** *An Introduction to Error Analysis*

Walker – *Astronomical Observations*

Most S.P.I.E. Conference Proceedings

and, when it comes out **Glass** — *The Infrared Astronomy Handbook*

We also recommend, for those interested, signing up for some of the free subscriptions one can get to trade magazines like *Photonics Spectra*, *NASA Tech Briefs* and *Laser Focus World.* These are fonts of information about the latest technologies and wares.

Problem Sets and Labs roughly every two weeks Some Guest Lectures Take Home FINAL - 1 month, open everything

Note that both JPH (495-7375) and I^2S (495-7100) have office hours by appointment.

Principles of Astronomical Measurement

Lecture 1. Introduction — The Real/Astronomical World

I. Basic Goals of Observational Astrophysics

(a) Measure flux, etc. from astronomical sources

(b) Understand the errors in such measurements

Ideal versus Real measurements and observations

Noise and Systematic Biases

Every astrophysical measurement is affected by noise and systematics. The object of the game for an experimentalist is to understand the nature of these effects, design experiments, samples, etc. that minimize their consequences, and honestly describe them when presenting the data or resluts from experiments.

(c) Apply measurements to

1. estimate parameters
2. test theories/hypotheses (Make 'em or break 'em)

II. Types of Measurements $I(X, Y, t, \lambda)$

A.k.a. How many things can you do with a photon?

(a) X, Y, $\frac{dX}{dt}$, $\frac{dY}{dt}$,

$\frac{d^2X}{dt^2}$, etc.

Size, Position, Shape

(b) F_λ, $\frac{dF_\lambda}{dt}$, Flux

(c) Polarization – Fraction/Direction

Stokes Parameters

You basically have position on the sky, motion, both on the sky (proper motion) and along the line-of-sight (radial velocity), sometimes acelleration (e.g. visual binary orbits, superluminal sources, maser proper motions), flux or brightness, and if the source is bright enought, flux density or a spectrum or spectral energy distribution, and last but not least, polarization.

III. Types of Measurer !!!!

- (a) Wavelength Specific / Technique Specific
- (b) Problem Specific
- (c) Eclectic

In the earliest days of a field such as astronomy, it is often the case that new techniques are brought into the field from other disciplines. Classic examples are Radio Astronomy, where the earliest observational techniques came from physics and electrical engineering, and High Energy Astrophysics and Infrared Astronomy, where techniques, and scientists (!) migrated into the field from nuclear and particle physics and solid state physics. Other examples include the shifting of people from applied mathematics and even computer sciences into astronomy. (That's also *not* to say that astronomers don't sometimes shift into other fields).

Generally, the first few generations of such scientists are technique specific — "radio" astronomers, "infrared" astronomers, etc. As the field matures, people become more problem oriented, e.g. cosmologists, stellar astrophysicists, planetary astronomers and people studying star formation. A local example of this categorization is the seven Divisions of CfA:

AMP	Atomic and Molecular Physics	a (+b+c)
HEA	High Energy Astrophysics	a
OIR	Optical In Infrared Astronomy	a
PS	Planetary Sciences	b
RG	Radio and Geoastronomy	a
SSP	Solar and Stellar Physics	b
TA	Theoretical Astrophysics	c

IV. Units and Definitions (cgs with astronomy modifications)

Flux — ergs s^{-1} cm^{-2}

Flux Density — ergs s^{-1} cm^{-2} Hz^{-1}

Specific Intensity — ergs s^{-1} cm^{-2} Hz^{-1} $Ster^{-1}$

= Brightness

in all of these, Hertz $\rightleftharpoons$ Angstroms $\rightleftharpoons$ cm $\rightleftharpoons$ Kev

and Watts $\rightleftharpoons$ ergs s^{-1}

also

$$\lambda\nu = c \qquad \text{and} \qquad E = h\nu = \frac{hc}{\lambda}$$

so as $\lambda \Uparrow$ $E \Downarrow$ $\nu \Downarrow$, and

as $\nu \Uparrow$ $E \Uparrow$ $\lambda \Downarrow$.

and

$$c = 2.997925 \times 10^{10}\ cm\ s^{-1}$$
$$h = 6.6262 \times 10^{-27}\ cm^3\ g^{-1}\ s^{-2}$$

Other conversion factors:

$$1\AA \;=\; 10^{-8}cm \;=\; 10^{-10}m$$
$$1\mu \;=\; 10^{-4}cm \;=\; 10^{-6}m \;=\; 10,000\AA$$
$$1\ ev \;=\; 1.60\times 10^{-12}erg \qquad 1\ kev \;=\; 12.4\AA$$
$$1\ cm \;=\; 30\ Ghz \qquad 21\ cm \;=\; 1430\ Mhz$$

V. More Definitions

(a) Signal — Flux, Photons from Astronomical Source

(b) Noise — Variations Induced by many Things

Photon Statistics

Electronic Noise

Background Sky, etc.

(c) Quantum Efficiency

$$\textbf{Responsive Quantum Efficiency (RQE)} \;=\; N'/N$$

where N' is number of detected photons (or flux) and N is the number if incident photons (or flux)

$$\textbf{Detective Quantum Efficiency (DQE)} \;=\; \left(\frac{S/N_{out}}{S/N_{in}}\right)^2$$

where S/N is the signal to noise and *in* and *out* refer to input and output.

These are extremely important concepts! As we shall see, a detector with great RQE but poor noise characteristics may be much worse for your application than one with the reverse. Also note that detector manufacturers will rarely quote you DQE, for obvious reasons.

VI. Other Notes

Each wavelength regime has its own units !

Gamma Ray Mev, Tev

X-Ray kev

UV, Optical Å, **magnitudes**

IR μ, mm, cm^{-1}

Radio mm, cm, m, Ghz, Mhz

Brightness Temperature

Magnitudes are referred to a standard star or stars (usually Vega, an A0 main sequence Star)

$$m \;=\; -2.5log(F) \;+\; constant$$

or

$$m_1 - m_2 \;=\; -2.5log(F_1/F_2)$$

0th Apparent Magnitude Visual (V) $\rightarrow$ 3.39 $\times 10^{-9}$ ergs cm^{-2} s^{-1} Å^{-1}

$\sim$ 950 photons cm^{-2} s^{-1} Å^{-1}

$\sim$ 3.39 $\times 10^{-12}$ Watt cm^{-2} μ^{-1}

$\sim$ 3.29 $\times 10^{-23}$ Watt m^{-2} Hz^{-1}

0th Magnitude Absolute Bolometric $\sim$ 3.0 $\times 10^{35}$ ergs s^{-1}

Why MAGNITUDES?

Everything is "relative." Magnitudes have their place in astronomy because the relative brightnesses of things can be measured quite accurately (if they don't change) but absolute fluxes are extremely hard to come by. Precisions of millimagnitudes are nouw routine in stellar photometry ($\sim$ 0.1%), but absolute calibrations, as we shall discuss later, are rarely good to better than 5% and often good only to 10%. Those astronomers wishing to use precision measures stick to magnitudes, and, only when it doesn't matter or when we need to move into the realm of astrophysics where real energy units are necessary, do we use watts/m^2/s/Hz or whatever. Ditto for surface brightness measures where the SI unit has essentially no relevance for astronomical measurements.

My apologies, but "BEWARE" SI units — some are rational but many are not:

The *Candela* is the SI unit of luminous intensity, defined as 1/60th of the normal intensity of 1 square cm of a blackbody at the melting point (solidification temperature) of platinum ($\sim$1772°C = 2044°K). A point source of one Candela intensity radiates 1 *lumen* into a solid angle of one steradian.

The *Nit* is the measure of luminance = 1 candela m^{-2}. Which means that surface brightness, which astronomers usually quote as magnitudes per square-arc-second should be quoted in Nits —

$$0\; magnitude/\square'' \;=\; 1.09 \times 10^5 \; Nits.$$

For reference, a dark night sky at V is $\sim$ 21 mag $\square''$, or about 4.33 $\times 10^{-4}$ Nits.

The night sky brightness is also sometimes quoted in either Rayleighs or in S_{10} units. One Rayleigh is defined as $\frac{1}{4\pi}$ 10^6 photons cm^{-2} s^{-1} ster^{-1}, and surface brightness is usually quoted in Rayleighs per Å. S_{10} units are the number of 10th magnitude stars per square-degree.

So the visible band dark night sky brightness at most American observatories is $\sim 21.0_V\ mag/\square''$ which:

$$
\begin{aligned}
&= \ 4.33 \times 10^{-4}\ Nits \\
&= ???magnitude/\square^\circ \\
&= ???\ S_{10} \qquad\qquad\qquad = ???\ Rayleigh\,\AA^{-1} \\
&= ???\ photons\ s^{-1}\ cm^{-2}\ \AA^{-1}\ ster^{-1} \\
&= ???\ photons\ s^{-1}\ cm^{-2}\ \AA^{-1}\ arcsec^{-2}
\end{aligned} \qquad (\sim 2)
$$

Your problem for next Monday is to fill in the ??? above.

One final note — the "Philosophy" of the course:

(1) Be *honest* in the evaluation of signal-to-noise and statistical significance.

(2) Be *careful* when explaining them to others or when using other's data.

(3) Know how your instruments work; Know your observers.

Also something to consider whether you're bound to be an experimentalist or a theorist: my ten most favorite words, spoken or written as necessary! (Useful in everyday life as, well.)

I don't know.

I was wrong.

It can be fixed!