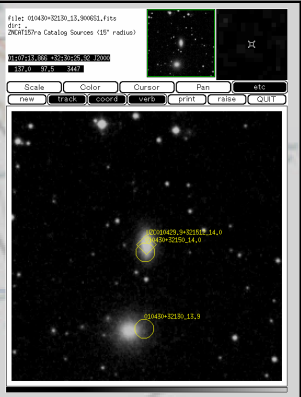
Astrometry in Information systems

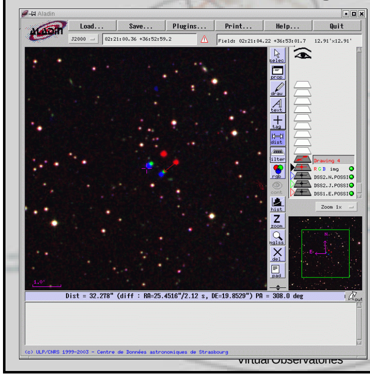
Lecture Series on Virtual Observatories

Why Astrometry

- Comparison
  - Images
  - Catalogs
- Identification of sources

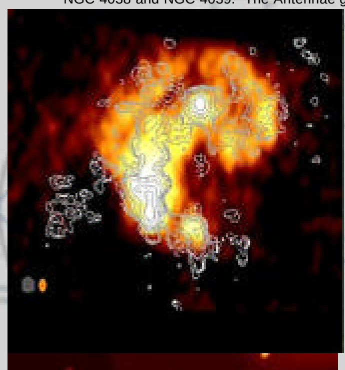


Astrometry Why



Estimation of the proper motion of ** WNO7:
32 .278''/(1987.751-1951.839)
=0.9''/yr

NGC 4038 and NGC 4039. The Antennae galaxies



Why Astrometry

X-Ray

Visible DSS

Optical AAO

Optical color

Infrared

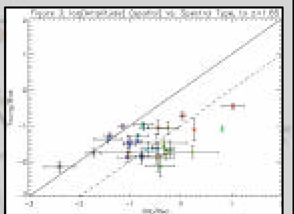
Spitzer

IRAS

Radio

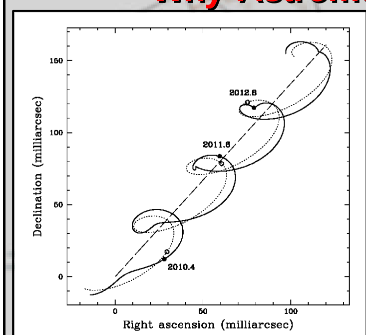
Why Astrometry

The two-point correlation function is an important measure of structure in the universe. In its angular form, *w*(?), it is defined by the expression d*P* = *N*[1+*w*?)]dO where d*P* is the probability of finding a second object at an angular separation of ? from a given object within an area of dO, and *N* is the mean object density (per steradian). The spatial correlation function can be obtained by converting from angular to spatial separations. The correlation function represents an "excess probability" above what would be expected for a random distribution of equivalent density.



The amplitude of the correlation function (the intercept of the best-fit line) is plotted for two different spectral type bins. The *x*-axis corresponds to old (red) galaxies, while the *y*-axiscorreseponds to young (blue) galaxies. Each point represents a particularredshift bin. Points would fall along the solid line if correlation amplitude were the same for both groups and would fall along the dashed line if amplitude were ten times larger for old (red) galaxies. Note that old (red) galaxies appear to be more strongly correlated and that their correlation increases with redshift.

Why Astrometry

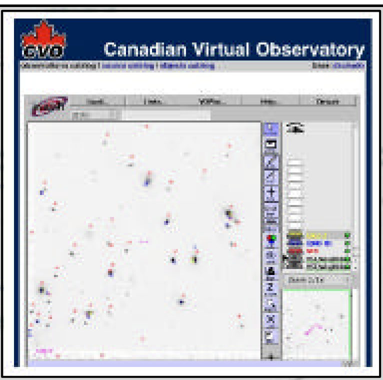


Stellar Planet Survey (STEPS)
30 M stars

Astrometric Search for Planets Encircling Nearby Stars (ASPENS)
100 stars

2 mas: 10 M_J in 4 years
1 M_J in 15 years

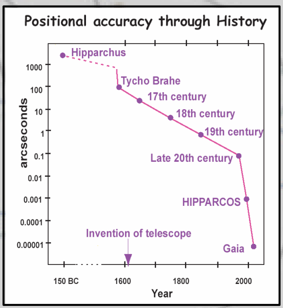
Figure 1. An example of the result of a basic VO query looking for correspondence between various catalogs. The "x" symbols are from NED, the diamonds from USNO-B, and the squares from the Guide Star Catalog. There are both random and systematic errors in the positions from these sources so that automated schemes of cross-identifying sources are difficult to implement.



Astrometry History

- in 129 BC the Greek astronomer Hipparchus completed a catalog of a thousand stars
  - naked eye observations
  - relative brightness
  - position with accuracy of one degree
- nothing changed until 16th century whereTycho Brahe using a variety of calibrated instruments like a sextant and mural quadrant
  - accuracy one minute of arc
- in 1609 the telescope was invented but did not help much as angular measurements were not easy
- in the 17th century afilar micrometer was invented allowing to measure the angular distance by means of the two wires
- in the 18th century knowledge of materials allowed engraving scales to a high precision
  - accuracy improved to arcseconds
  - allowed detection of aberration, proof of the Earth moving thrcugh space
- in the 19th century even better engraving was possible allowing detection of parallaxes
  - first distance scale to local universe
- in the 20th century photographic plates enabled high precision a strometry
  - accuracy imporvedto 0.1 arcseconds
  - limited by atmosphere
  - hipparcos improved accuracy to 1 milliacrsecond

Astrometric Reference Catalogs



Astrometric Reference Frames

- " SUPERGALACTIC":
  - De Vaucouleurs Supergalactic coordinates. It was designed to have its equator aligned with the **supergalactic plane**, a major structure in the local universe formed by the preferential distribution of nearby galaxy clusters (such as the Virgo cluster, the Great Attractor and the Pisces-Perseus supercluster).
  - The north supergalactic pole (SGB=90°) lies at galactic coordinates (*l*=47.37°, *b*=+6.32°). In the equatorial coordinate system (epoch J2000), this is approximately (RA=18.9 h, Dec=+15.7°).
  - The zero point (SGB=0°, SGL=0°) lies at (*l*=137.37°, *b*=0°). In J2000 equatorial coordinates, this is approximately (2.82 h, +59.5°).
- "GALACTIC":
  - Galactic coordinates (IAU 1958). The galactic coordinates define a spherical coordinate system with the Sun at the center and a plane paralle to the general orientation of the Milky Way galaxy's central plane as the galactic equator.
  - In 1959, the IAU defined a standard of conversion between the Equatorial coordinate system and galactic coordinate system. Accordingly, the Milky Way's north galactic pole is exactly RA 12h51m26.282s, Dec 27°0742.01?.
  - The "zero of longitude" point on the galactic coordinates was ca librated to 17h45m37.224s, -28°56'10.23? (J2000), and its J2000 position ang le is 122.932°. Since the plane of the galactic equator lies above the plane through the center of the galaxy the galactic center is offset from the longitudinal origin and is located at 17h45m40.04s, -29°00'28.1? (J2000).

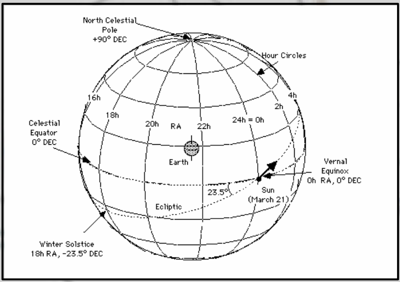
Astrometric Reference Frames

- "ECLIPTIC":
  - Ecliptic coordinates (IAU 1980), referred to the ecliptic and mean equinox specified by the qualifying Equinox value. The **ecliptic coordinate system** is a celestial coordinate system that uses the ecliptic for its fundamental plane. The ecliptic is the path that the sun appears to follow across the sky over the course of a year. It is also the projection of the Earth's orbital plane onto the celestial sphere.
- "HELIOECLIPTIC":
  - Ecliptic coordinates (IAU 1980), referred to the ecliptic and mean equinox of J2000.0, in which an offset is added to the longitude value which results in the centre of the sun being at zero longitude at the date given by the Epoch attribute.

Astrometric Reference Frames

- "FK5" or "EQUATORIAL":
  - Is barycentric equatorial coordinate system.
  - Should be qualified by an Equinox value.
  - The system is based on absolute and quasi-absolute catalogues with mean epochs later than 1900;
    - Consist of about 85 catalogues giving observations from 1900 toabout 1980.
    - Observations were made with meridian circles, vertical circles, transit instruments, and astrolabes.
  - The major changes involved in the transition from the FK4 to FK5 are as follows:
    - The determination of systematic and individual corrections to th e mean positions and proper motions of the FK4, computed on the mean equinox and equator B1950.0, using Newcomb's constant of precession.
    - The new values for theprecessional quantities were introduced within the transformation of the mean positions and proper motions from B1950.0 to J2000.0 (Lieske et al. 1977).
    - The elimination of the error in the FK4 equinox, as shown by Fricke (1982).
    - The introduction of the IAU(1976) System of Astronomical Constants (see *Trans. IAU*, 1977, **XVIB**, 52-67).
- "FK4":
  - The old barycentric equatorial coordinate system
  - Should be qualified by an Equinox value.
  - Underlying model on which this is based is non-inertial and rotates slowly with time, so for accurate work FK4 coordinate systems should also be qualified by an Epoch value.

Astrometric Reference Frames



The Earth precesses or wobbles on its axis, once every 26,000 years. Unfortunately, this means that the Sun crosses the celestial equator at a slightly different point every year, so that our "fixed" starting point changes slowly - about 40 arc-seconds per year.

Ecliptic and equatorial coordinates

Astrometry Reference Frames

- Equinox
  - An **equinox** is the event when the Sun can be observed to be directly above the equator.
  - Is used to qualify those celestial coordinate systems which are notionally based on the ecliptic (the plane of the Earth's orbit around the Sun) and/or the Earth's equator.
    - Both of these planes are in motion and their positions are difficult to specify precisely.
    - These, together with the point on the sky that defines the coordinate origin (the intersection of the two planes termed the "mean equinox") move with time according to some model which removes the more rapid fluctuations.
  - The position of a fixed source expressed in any of these coordinate systems will appear to change with time due to movement of the coordinate system itself (rather than motion of the source). Such coordinate systems must therefore be qualified by a moment in time (the "epoch of the mean equinox" or "equinox" for short) which allows the position of the model coordinate system on the sky to be determined.
  - The default Equinox value is
    - B1950.0 (Besselian) for the old FK4-based coordinate systems
    - J2000.0 (Julian) for others

Astrometric Reference Frames

- Epoch:
  - an **epoch** is a moment in time for which celestial coordinates or orbital elements are specified. In the case of celestial coordinates, the position at other times can be computed by taking into account precession and proper motion.
  - This attribute is used to qualify the coordinate systems by giving the moment in time when the coordinates are known to be correct.
  - Often, this will be the date of observation, and is important in cases where coordinates systems move with respect to each other over the course of time.

Astrometric Reference Frames

- ICRS: The International Celestial Reference System
  - Realised through the Hipparcos catalogue. Whilst not an equatorial system by definition,
  - Very close to the FK5 (J2000) system and is usually treated as an equatorial system.
  - Distinction between ICRS and FK5 (J2000) only becomes important when accuracies < 50 milli-arcseconds.
  - ICRS need not be qualified by an Equinox value.
  - The directions of the ICRS pole and right ascensions origin are maintained fixed relative to the quasars within +/- 20 microarcseconds.
  - The ICRS complies with the conditions specified by the 1991 IAU Recommendations.
    - Its **origin** is located at the barycenter of the solar system through appropriate modelling of VLBI observations in the framework of General Relativity.
    - Its **pole** is in the direction defined by the conventional IAU models for precession (Lieske et al., 1977) and nutation (Seidelmann, 1982).
    - Its **origin of right ascensions** was implicitly defined by fixing the right ascension of 3C 273B to the Hazard et al. (1971) FK5 value transferred at J2000. 0.

Astrometry Reference Catalogs

ASTROMETRIC DATA: currently recommended
Hipparcos
TYCHO-2
UCAC2: USNO CCD Astrograph Catalog, 2nd release
UCAC2 Bright Star Supplement
USNO B1.0
ASTROMETRIC DATA: superseded or not recommended
FK5
IRS: International Reference Stars
ACRS
PPM
TYCHO-1
ACT Reference Catalog
Tycho Reference Catalogue
AC: Astrographic Catalogue
UCAC1: USNO CCD Astrograph Catalog, 1st release
GSC 1.2: Guide Star Catalog version 1.2
USNO A2.0
USNO SA2.0
GSC 2.2: Guide Star Catalog version 2.2

INFRARED SOURCES
CPIRSS: Catalog of Positions for Infrared Stellar Sources
2MASS: Two-Micron All Sky Survey
CATALOGS FORTHCOMING
UCAC (final)
DOUBLE STAR CATALOGS
WDS: Washington Double Star Catalog
6th Orbit Catalog
MAGNITUDES AND SPECTRAL TYPES
HD: Henry Draper Catalog
PARALLAXES
Hipparcos Catalogue
General Catalogue of Trig. parallaxes
VARIABLE STARS
Hipparcos and Tycho-2 Catalogues
GCVS: General Catalog of Variable Stars

Astrometric Reference Catalogs

- USNO-A2.0 has adopted the ICRS as its reference frame, and uses the ACT catalog (Urban et al. 1997) for its astrometric reference catalog.
- The Hipparcos satellite established the ICRS at optical wavelengths, but stars in the Hipparcos catalog are saturated on deep Schmidt survey plates as are the brighter Tycho catalog stars. Fortunately, the fainter Tycho stars have measurable images, so each survey plate can be directly tied to the ICRS without an intermediate astrometric reference frame.
- The proper motions contained in the ACT catalog are more accurate than those in the Tycho catalog, so the ACT was adopted as the reference catalog.
- USNO-A1.0 use the Guide Star Catalog v1.1 as its astrometric reference catalog, and the availability of the ACT was the driving force behind the compilation of USNO-A2.0.

Astrometric Reference Catalogs

- UCAC2
  - is a high density, highly accurate, astrometric catalog of
  - 48,330,571 stars
  - covering the sky from -90 to +40 degrees in declination and going up to +52 degrees in some areas.
  - Proper motions and photometry are provided for all stars.
  - Positions and proper motions are on the ICRS (International Celestial Reference System) and given at the epoch J2000.0 and are accurate to 20 mas for stars in the 10 to 14 magnitude range are obtained. At the limiting magnitude of R=16 the catalog positions have a standard error of 70 mas.
  - Photometry errors on the order 0.1 to 0.3 magnitudes in a single, non-standard color
- USNO-B1.0
  - is an all-sky catalog that presents
  - positions, proper motions, magnitudes in various optical passbands, and star/galaxy estimators
  - for 1,042,618,261 objects derived from 3,643,201,733 separate observations.
  - provide all-sky coverage, completeness down to V = 21,
  - 0.2 arcsecond astrometric accuracy at J2000,
  - 0.3 magnitude photometric accuracy in up to five colors
  - 85% accuracy for distinguishing stars from non-stellar objects.

Astrometric Reference Catalogs

Tycho

- Epoch is J2000.0
- Reference system ICRS coincidence with ICRS (1) ±0.6 mas deviation from inertial (1) ±0.25 mas/yr
- Number of entries 2,539,913
- Astrometric standard errors (2) V_T < 9 mag 7 mas
  - all stars, positions 60 mas
  - all stars, proper motions 2.5 mas/yr
- Photometric std. errors (3) on V_T < 9 mag 0.013 mag
  - all stars 0.10 mag
- Star density
  - b= 0 deg 150 stars/sq.deg.
  - b= ±30 deg 50 stars/sq.deg.
  - b= ±90 deg 25 stars/sq.deg.
- Completeness to 90 per cent V ~ 11.5 mag
- Completeness to 99 per cent V ~ 11.0 mag

Astrometric Reference Catalogs

- Hipparcos Catalogue
  - includes 118218 preselected entries brighter than V 12.4
  - 117955 with associated astrometry
  - 118204 with associated photometry.
  - Observations were made from 1989.85 to 1993.21, with a mean epoch of close to J1991.25, adopted as the catalogue epoch.
  - Standard errors are functions of magnitude and ecliptic latitude.
    - Right Ascension 0.77 mas
    - Declination 0.64 mas
    - Parallax 0.97 mas
    - Proper motion RA 0.88 mas/yr
    - Proper motion DEC 0.74 mas/yr
  - Systematic parallax errors are estimated to be smaller than 0.1 mas
  - The coincidence with the adopted reference system (ICRS) is estimated to be within 0.6 mas about all 3 axes, and the deviation from inertial in the range 0.25 mas/yr, also about all 3 axes

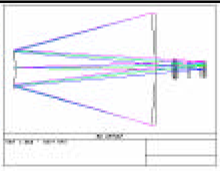


Fig. 1 - VST complete optical layout of telescope with one lens and the ADC, with a curve dewar window

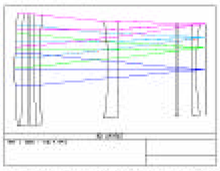
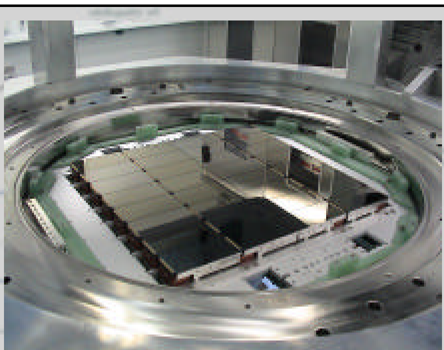
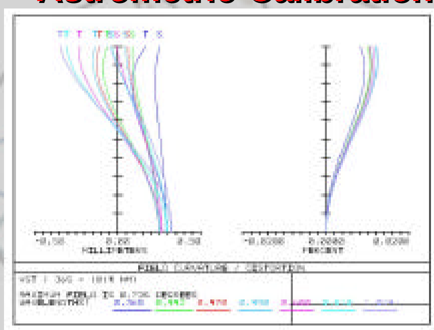


Fig. 2 - VST zoom of the optical layout of the corrector with one lens and the ADC, with a curve dewar window



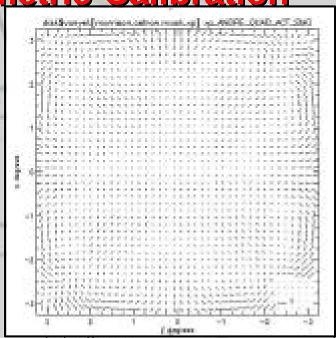
Astrometric Calibration



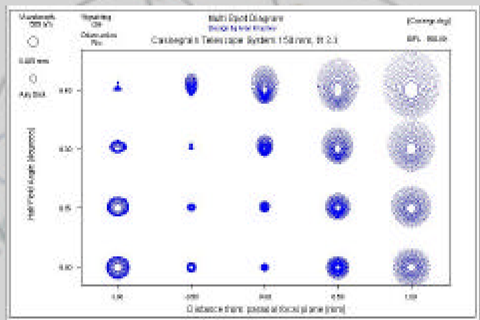
Astrometric Calibration

Palomar Sky SurveyPlate

Optical distortion map

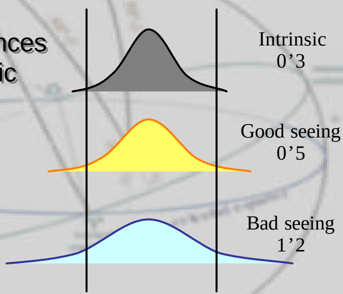


Astrometric Calibration

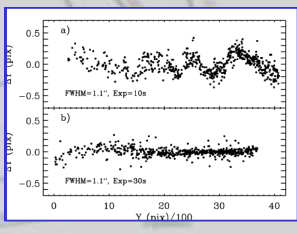


Intrinsic Positional Accuracy

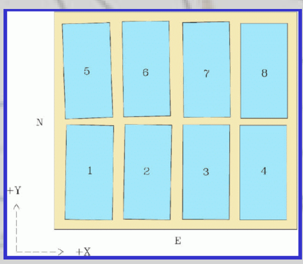
- Seeing influences the astrometric accuracy



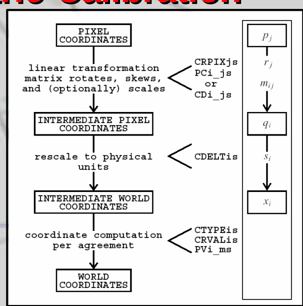
Intrinsic Positional Accuracy



Astrometric Calibration

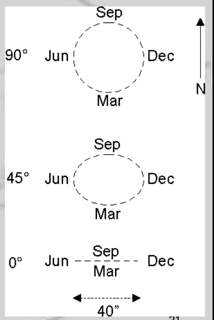


Astrometric Calibration



Astrometric Calibration

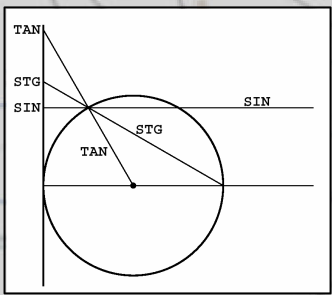
- Aberration
  - Annual aberration is due to the revolution of the Earth around the Sun.
  - Planetary aberration is the combination of aberration and light-time correction.
  - Diurnal aberration is due to the rotation of the Earth about its own axis.
  - Secular aberration is due to the motion of the Sun and solar system relative to other stars in the galaxy



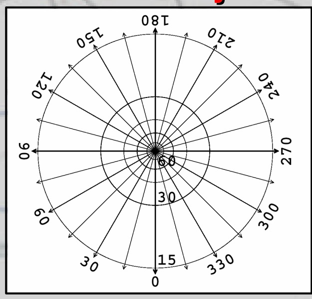
Astrometric Calibration

- Atmospheric Refraction
  - The deviation of light or other electromagnetic wave from a straight line as it passes through the atmosphere due to the variation in air density as a function of altitude
  - The atmospheric refraction is zero in the zenith, is less than 1' (one arcminute) at 45° altitude, still only 5' at 10° altitude

Astrometric Projections



Astrometric Projections



Astrometric Calibration

- Errors
  - Centering errors

$$d\xi = c_1 + b_1\eta + \xi (c_1 \xi + f_1 \eta)$$
$$d\eta = f_1 + b_1 \xi + \eta (c_1 \xi + f_1 \eta)$$

  - Const: independent of object position
  - First order: rotation 1" -> 0"02
  - Second order: 1" -> 0"02 displacement 1° off-axis

  - Aberration

$$d\xi = c_2 + a_1 \xi + ½\, c_2 (\xi^2 + \eta^2)$$
$$d\eta = f_2 + a_1 \eta + ½\, f_2 (\xi^2 + \eta^2)$$

  - Const: displacement direction dependent
  - First order: scaling parameter
  - Second order: 1" -> 0"006 displacement 1° off-axis

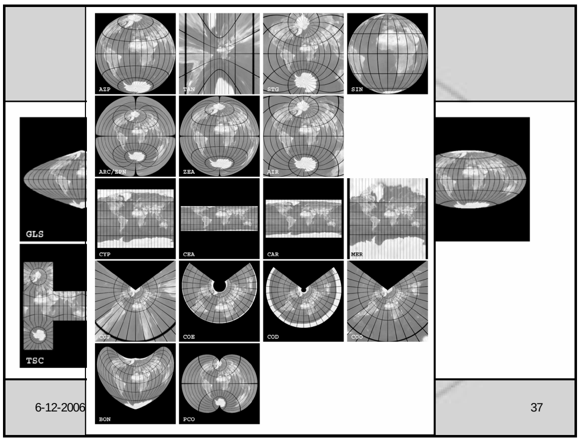
  - Refraction

$$d\xi = k_0 (1 + \xi^2 + \eta^2)/(1 + \xi_o \xi + \eta_o \eta)\,(\xi_0 - \xi)$$
$$d\eta = k_0 (1 + \xi^2 + \eta^2)/(1 + \xi_o \xi + \eta_o \eta)\,(\eta_0 - \eta)$$

  - Const: displacement
  - First order: smaller in scale
  - Second order: slightly larger than aberration

Astrometry Projections

AZP	90	Zenith perspective
TAN	90	Gnomic
SIN	90	Othographic
STG	90	Stereographic
ARC	90	Zenith equidistant
ZPN	90	Zenith polynomial
ZEA	90	Zenith equal-area
AIR	90	Airy
CYP	0	Cylindrical perspective
CAR	0	Cartesian
MER	0	Mercator
CEA	0	Cylindrical equal are
COP	90	Conical perspective
COD	90	Conical equidistant
COE	90	Conical equal-are
COO	90	Conical orthomorphic
BON	90	Bonne's equal aera
PCO	0	Polyconic
GLS	0	Sinosoidal
PAR	0	Parabolic
AIT	0	Hammer - Aitoff
MOL	0	Mollweide
CSC	0	Cobe Quadrilateralized SphericalCube
QSC	0	Quadrilateralized Spherical Cube
TSC	0	Tangential Spherical Cube



Astrometric Projections

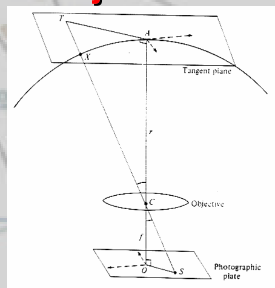
Gnomonic projection

Forward

(a,ß) -> (?,?)

Backward

(?,?) -> (a, ß)

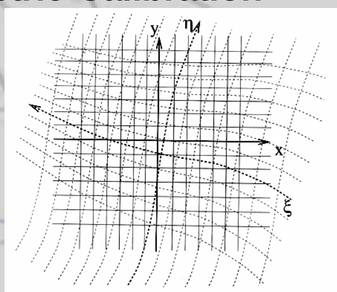


Astrometric Calibration

- Single field
  - Polynomial description

$\xi(x,y) = a + \Sigma\, b_{ij}\, x^i y^j$

$\eta(x,y) = c + \Sigma\, d_{ij}\, x^i y^j$



Astrometric Calibration

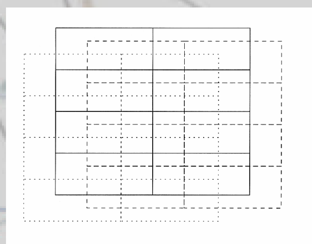
- Overlap fields
  - Independent set of params/field
  - Dependence of b and d with field

$\xi(x,y) = a + \Sigma\Sigma\, b_{ijk}\, x^i y^j f^k$

$\eta(x,y) = c + \Sigma\Sigma\, e_{ij}\, x^i y^j f^k$

  - Spatial terms Chebychev polynomes

$P_{n+1} - f\, R_n(f) + P_{n-1}(f) = 0$



Astrometric Calibration

- Least Squares
  - Pairing
    - Extracted objects with reference catalog
      - USNO-A2 100 sources (RMS 0"3)
      - GSC 8 source (RMS 0"3)
      - Tycho 1 source (RMS 0"03)
      - Hipparcos 0.1 source (RMS 0"003)
      - PPM 0.3 source (RMS 0"1)
    - Extracted objects in overlap
      - Internal extraction precision RMS 0.1 pixel (< 0"03)
  - Minimization
    - Sum of squared differences weighted with positional precision knowledge
  - Iterate
    - Kappa-Sigma clipping > 4σ excursions
      - Remove erroneaus pairrings
      - Minimize cenering errors

Astrometric Calibration

$$\zeta(x,y,f) = a_f + \sum_{i+j=1}^{i+j=p} \sum_{k=0}^{n} b_{ijk} x^i y^j f^k$$

$$\eta(x,y,f) = c_f + \sum_{i+j=1}^{i+j=p} \sum_{k=0}^{n} d_{ijk} x^i y^j f^k$$

Astrometric Calibration

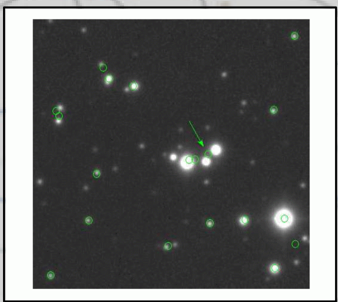
$$S = \sum_{f=1}^{n_{field}} \sum_{i=1}^{n_{ref}^{f}} \frac{\left\| \zeta(x_i, y_i, f) - \zeta_i^f \right\|^2}{\sigma_{mes}^2(i) + \sigma_{cat}^2(i)} + \sum_{f=1}^{n_{field}} \sum_{i=1}^{n_{ref}^{f}} \frac{\left\| \eta(x_i, y_i, f) - \eta_i^f \right\|^2}{\sigma_{mes}^2(i) + \sigma_{cat}^2(i)}$$
$$+ \sum_{f_1=1}^{n_{field}} \sum_{f_2=1}^{n_{field}} \sum_{i=1}^{n_{over}^{f_1 f_2}} \frac{\left\| (\zeta(x_i, y_i, f_1) - \zeta(x_i, y_i, f_1)) - (\zeta_i^{f_1} - \zeta_i^{f_2}) \right\|^2}{\sigma_{mes}^2(i, f_1) + \sigma_{mes}^2(i, f_2)}$$
$$+ \sum_{f_1=1}^{n_{field}} \sum_{f_2=1}^{n_{field}} \sum_{i=1}^{n_{over}^{f_1 f_2}} \frac{\left\| (\eta(x_i, y_i, f_1) - \eta(x_i, y_i, f_1)) - (\eta_i^{f_1} - \eta_i^{f_2}) \right\|^2}{\sigma_{mes}^2(i, f_1) + \sigma_{mes}^2(i, f_2)}$$

Astrometric Calibration

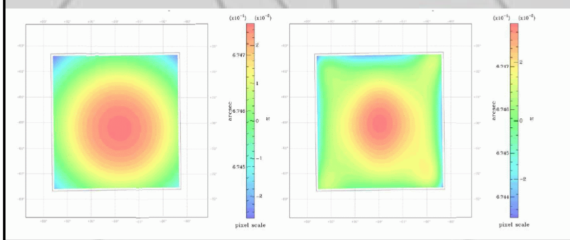
$$S = (A \cdot X - B)^T \cdot (A \cdot X - B)$$

$$\begin{aligned}
X_i &= a_f \text{ for } i \leq n_f \\
X_i &= b_p \text{ for } i > n_f \\
\\
B_i &= \zeta_{if_i} \text{ for } i \leq N_{ref} \\
B_i &= (\zeta_{if_i^1} - (\zeta_{if_i^2}) \text{ for } i > N_{ref} \\
\\
A_{ij} &= \delta_{jf_i}/\sigma_i \text{ for } i \leq N_{ref} \text{ and } j \leq n_f \\
A_{ij} &= f(x_i, y_i, f_i)/\sigma_i \text{ for } i \leq N_{ref} \text{ and } j > n_f \\
A_{ij} &= (+\delta_{jf_i^1} - \delta_{jf_i^2})/\sigma_i \text{ for } i > N_{ref} \text{ and } j \leq n_f \\
A_{ij} &= (f(x_i, y_i, f_i^1) - f(x_i, y_i, f_i^2))/\sigma_i \text{ for } i > N_{ref} \text{ and } j > n_f
\end{aligned}$$

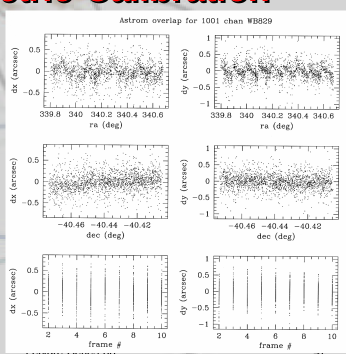
Astrometric Calibration



Astrometric Calibration

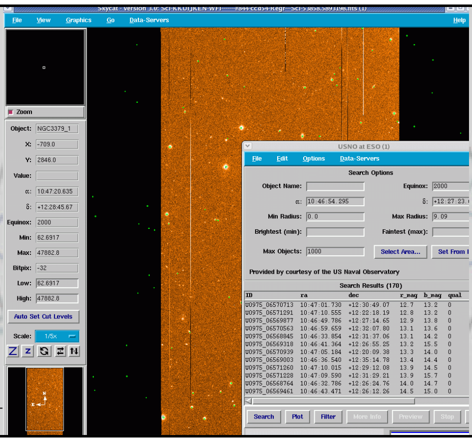


Astrometric Calibration

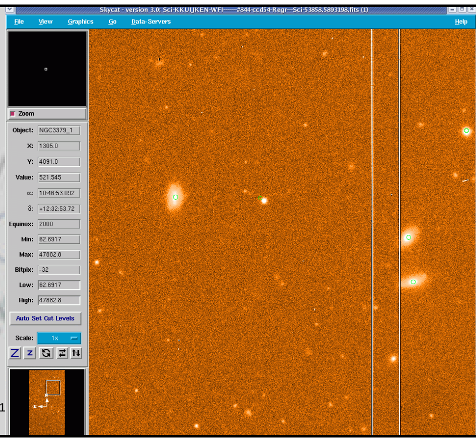


Astrometry Basics

$$\begin{pmatrix} x \\ y \\ z \\ \vdots \end{pmatrix} = \begin{pmatrix} \texttt{CDELT1} & 0 & 0 & \dots \\ 0 & \texttt{CDELT2} & 0 & \dots \\ 0 & 0 & \texttt{CDELT3} & \dots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} \times$$
$$\begin{pmatrix} \texttt{PC001001} & \texttt{PC001002} & \texttt{PC001003} & \dots \\ \texttt{PC002001} & \texttt{PC002002} & \texttt{PC002003} & \dots \\ \texttt{PC003001} & \texttt{PC003002} & \texttt{PC003003} & \dots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix} \times$$
$$\begin{pmatrix} i - i_0 \\ j - j_0 \\ k - k_0 \\ \vdots \end{pmatrix} .$$



6- 49



6-1 50

Keyword	Use	Status	Comments
CRVALi	value at reference point	clarified	meaning of reference point forced by projection; no default.
CRPIXi	pixel of reference point	clarified	meaning of reference point forced by projection; no default.
CDELTi	increment at ref. point	clarified	meaning of reference point forced by projection; no default.
CROTAi	rotation at ref. point	deprecated	replaced by PCiiijjj .
CTYPEi	coordinate/projection type	clarified	for spherical coordinates, first 4 characters give "standard sys tem" used in
CRVALn ,			second 4 characters give type of projection as in Table 5; no default.
CUNITi	units of coordinate values	new	character -valued; keep it simple please; ignored for angles which are always
degrees			
PCiiijjj	coordinate increment	new	converts pixel number to pixels along true coordinates; default = 0(iii 6= jjj); = 1(iii = jjj).
CDiiijjj	coordinate increment	defined	synonym for PCiiijjj times CDELTndiagonal matrix; deprecated no default; – should not be written
CDi j	coordinate increment	defined	synonym for PCiiijjj times CDELTndiagonal matrix; deprecated no default; – should not be written
LONGPOLE pole;	coordinate rotation	new	longitude in the native coordinate system of the standard system's North
			default = 0ffi if ffi0 ? `0, = 180ffi otherwise.
LATPOLE	coordinate rotation	new	latitude in the native coordinate system of the standard system' s North pole; default (= 999) equivalent given by Eq. 7 with + taken.
PROJPm	projection parameter m	new	parameters required in some projections, see Table 5; no defaultfor m = 1, otherwise 0.
EPOCH	coordinate epoch	deprecated	replaced by EQUINOX.
EQUINOX FK5;	coordinate epoch	new	epoch of the mean equator and equinox in years; (Besselian if FK4, Julian if
			see Section 3 for defaults
MJD -OBS	date of observation	new	Modified Julian Date (JD - 2400000.5) of observation in days; default = DATE -OBS or, if missing, EQUINOX.
RADECSYS	frame of reference	new	string identifying the frame of reference of the equatorial coor dinates; default = 'FK4' for EQUINOX < 1984:0 and 'FK5' for >= 1984:0
CmVALi	value at reference point	new	(m = 2; 3; : : :9) secondary coordinate for axis i; no default.
CmPIXi	pixel of reference point	new	secondary coordinate description; no default.
CmELTi	increment at ref. point	new	secondary coordinate description; no default.
CmYPEi	coordinate/projection type	new	secondary coordinate description; no default.
CmNITi	units of coordinate values	new	secondary coordinate description; no default except angles are i n degrees.

Astrometry Basics

FITS Flexible Image Transport System

fixed logical record length of 2880 bytes
header records with an 80-byte keyword-equals-value substructure
header is followed by the header-specified number of binary data records
with optional extension records

CRVALn coordinate value at reference point
CRPIXn array location of reference point in pixels
CDELTn coordinate increment at reference point
CTYPEn axis tyoe (8 chars)
CROTAn rotation from stated coorinatetype

CTYPE is RA-- and DEC- equatorial coordinates
or GLON and GLAT galactic coordinates
or ELON and ELAT ecliptic coordinates
with projections
-SIN orthographic projection (radio synthesis)
or -TAN gnomonic projection (optical telescopes)
or -ARC zenithal equidistant projection (Schmid telescopes)
or -NCP orthographic projection (east-west radio interferometers)


```
SIMPLE  =                    T / Fits format
BITPIX  =                  -32 / bits per pixel
NAXIS   =                    2 / single image
NAXIS1  =                 2442 / x size
NAXIS2  =                 4881 / y size
DATE-OBS= '2000-04-04T03:12:13' / no comment
FLXSCALE=    6.05223407986e-13 / no comment
OBJECT  = 'NGC3379_1          ' / no comment
ZEROPNT =        30.5452107082 / no comment
ZPNTERR =        1.00000827428 / no comment
INSTRUME= 'WFI                ' / no comment
TELESCOP= 'MPI-2.2            ' / no comment
TEL_LAT =             -29.2543 / no comment
TEL_LONG=             -70.7346 / no comment
TEL_ELEV=               2335.0 / no comment
TEL_ZONE=                  4.0 / no comment
CHIP_ID = 'ccd54              ' / no comment
FILT_ID = '#844               ' / no comment
CTYPE1  = 'RA---TAN           ' / no comment
CRVAL1  =          162.3913043 / no comment
CRPIX1  =             -10469.0 / no comment
CTYPE2  = 'DEC--TAN           ' / no comment
CRVAL2  =          12.44680851 / no comment
CRPIX2  =               2250.0 / no comment
CD1_1   =     -5.555555638e-05 / no comment
CD1_2   =                  0.0 / no comment
CD2_1   =                  0.0 / no comment
CD2_2   =      5.555555638e-05 / no comment
STATMIN =       -7183.23876953 / no comment
STATMAX =        57059.4921875 / no comment
STATMEAN=        537.706895159 / no comment
STATDEV =        397.969127936 / no comment
STATMED =        534.767578125 / no comment
OBS_DATE= '2000-04-04T03:12:13' / no comment
OBS_NAME= 'Unknown            ' / no comment
OBS_TYPE= 'Unknown            ' / no comment
OBS_ID  =                   -1 / no comment
OBS_PID = 'Unknown            ' / no comment
TPL_DATE= '2000-04-04T03:12:13' / no comment
TPL_NAME= 'Unknown            ' / no comment
TPL_PURP= 'Unknown            ' / no comment
TPL_NEXP=                    1 / no comment
DATAMD5 = '5200f9c357c532e6c2c6e1043e8e92be' / MD5 checksum
END
```



```
NAXIS   =                    0          / # of axes in data array
INSTRUME= 'WFI     '                    / Instrument used
TELESCOP= 'MPI-2.2 '                    / ESO Telescope Name
OBJECT  = 'NGC3379_1'                   / Target description
OBSERVER= 'Saglia  '                    / Name of observer
ORIGIN  = 'ESO-LASILLA'                 / European Southern Observatory
PI-COI  = 'Saglia  '                    / Name(s) of proposer(s)
ORIGFILE= 'wfi58331.fits'               / Original File Name
EXPTIME =             299.9170          / Total integration time
RA      =           161.962560          / 10:47:51.0 RA (J2000) pointing
DEC     =             12.58236          / 12:34:56.4 DEC (J2000) pointing
DATE    = '2005-12-08T15:40:42.762'     / Date this file was written
DATE-OBS= '2000-04-04T03:12:13.825'     / UT date and time of observation at staLS
   =            40818.661         / 11:20:18.661 LST
UTC     =            11534.276          / 03:12:14.276 UTC
EQUINOX =               2000.0          / Standard FK5 (years)
RADECSYS= 'FK5     '                    / Coordinate reference frame
MJD-OBS =       51638.13349336          / MJD start (2000-04-04T03:12:13.826)
EXTEND  =                    T          / Extensions allowed
ARCFILE = 'WFI.2000-04-04T03:12:13.826.fits' / Archive File Name
UT      = '03:12:14.276'                / UT at start
ST      = '11:20:18.661'                / ST at start
AIRMASS =              1.35600          / Averaged air mass
IMAGETYP= 'OBJECT  '                    / Observation type
HIERARCH ESO OBS PROG ID     = '064.N-0030' / ESO program identification
HIERARCH ESO DPR DID         = 'ESO-VLT-DIC.DPR-1.3' / DPR Dictionary
.
.
.
XTENSION= 'IMAGE   '                    / Extension type
BITPIX  =                   16          / # of bits storing pix values
NAXIS   =                    2          / # of axes in data array
NAXIS1  =                 2142          / # pixels/axis
NAXIS2  =                 4128          / # pixels/axis
PCOUNT  =                    0          / Number of parameters per group
GCOUNT  =                    1          / Number of groups
EXTNAME = 'WIN1.CHIP1.OUT1'             / Extension name
CTYPE1  = 'PIXEL   '                    / Pixel coordinate system
CTYPE2  = 'PIXEL   '                    / Pixel coordinate system
CRVAL1  =                  1.0          / Ref pixel in X of full chip
CRVAL2  =                  1.0          / Ref pixel in Y of full chip
CRPIX1  =                 49.0          / Ref pixel of center of rotation
CRPIX2  =              -4097.0          / Ref pixel of center of rotation
CDELT1  =                  1.0          / Binning factor
CDELT2  =                  1.0          / Binning factor
BZERO   =              32768.0          / real=fits-value*BSCALE+BZERO
BSCALE  =                  1.0          / real=fits-value*BSCALE+BZERO
BLANK   =                32767          / Value used for NULL pixels
MJD-OBS =       51638.13349336          / MJD start (2000-04-04T03:12:13.826)
DATE    = '2000-04-04T03:17:51'         / Date this file was written
```

Astrometry in pipelines

- Source Extraction
  - Sextractor
  - DAOphot
  - IDL find
  - IRAF/STSDAS
- Astrometry
  - Individual routines
  - Separate software

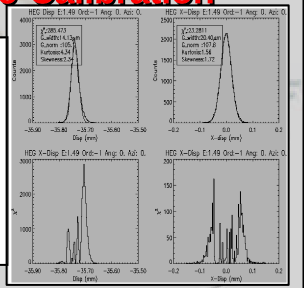
```
'X_IMAGE # Object position alongx',
'Y_IMAGE # Object position alongy',
'X2_IMAGE #Variance along x',
'Y2_IMAGE #Variance along y',
'XY_IMAGE #Covariance betweenx and y',
'ISOAREA_IMAGE #Isophotal area above Analysis threshold',
'BACKGROUND # Background at centroid position',
'FLAGS #Extraction flags',
'THRESHOLD #Detection threshold above background',
'FLUX_MAX #Peak flux above background',
'A_IMAGE #Profile RMS along major axis',
'B_IMAGE #Profile RMS along minor axis',
'THETA_IMAGE #Position angle (CCW/x)',
'ERRA_IMAGE # RMS position error along major axis ',
'FLUX_ISO #Isophotal flux',
'FLUXERR_ISO # RMS error for isophotal flux',
'MAG_ISO #Isophotal magnitude',
'MAGERR_ISO # RMS error for isophotal magnitude',
'FLUX_APER # Flux vectorwithin fixed circular aperture(s)',
'FLUXERR_APER # RMS errorvector for aperture flux(es)',
'MAG_APER #Fixed aperture magnitude vector',
'MAGERR_APER # RMS error vector for fixed aperture mag.',
```


Astrometric Calibration

$$\mathrm{X2} \;=\overline{x^2} = \frac{\sum_{i\in\mathcal{S}} I_i x_i^2}{\sum_{i\in\mathcal{S}} I_i} - \overline{x}^2,$$

$$\mathrm{Y2} \;=\overline{y^2} = \frac{\sum_{i\in\mathcal{S}} I_i y_i^2}{\sum_{i\in\mathcal{S}} I_i} - \overline{y}^2,$$

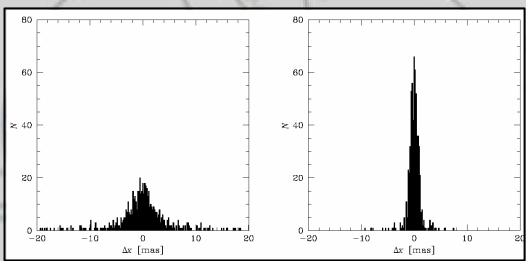
$$\mathrm{XY} \;=\overline{xy} = \frac{\sum_{i\in\mathcal{S}} I_i x_i y_i}{\sum_{i\in\mathcal{S}} I_i} - \overline{x}\,\overline{y},$$



Intrinsic Positional Accuracy

Modes of pixel distribution

Gaussian fit to pixel distribution



Astrometry WEBServices

- Astrometic Calibration example
  - http://dbview.astro-wise.org
- Coordinate conversion
  - http://cdsweb.u-strasbg.fr/cdsws/astroCoo.gml
- UCDs
  - **pos** (positional data)
  - This section describes all quantities related to the position of an object on the sky:
    - Angular coordinates, and projections from spherical to rectangular systems.
    - Angular measurements in general (the angular size of an object is in this section, its linear size is in the **phys** section).
    - The WCS FITS keywords.

Q	pos	Position and coordinates
Q	pos.angDistance	Angular distance, elongation
Q	pos.angResolution	Angular resolution
Q	pos.az	Position in alt-azimutal frame
Q	pos.az.alt	Alt-azimutal altitude
Q	pos.az.azi	Alt-azimutal azimut
Q	pos.az.zd	Alt-azimutal zenith distance
S	pos.barycenter	Barycenter
S	pos.bodyrc	Body related coordinates
Q	pos.bodyrc.alt	Body related coordinate (altitude on the body)
Q	pos.bodyrc.lat	Body related coordinate (latitude on the body)
Q	pos.bodyrc.long	Body related coordinate (longitude on the body)
S	pos.cartesian	Cartesian (rectangular) coordinates
Q	pos.cartesian.x	Cartesian coordinate along the x -axis
Q	pos.cartesian.y	Cartesian coordinate along the y-axis
Q	pos.cartesian.z	Cartesian coordinate along the z-axis
Q	pos.eq.dec	Declination in equatorial coordinates
Q	pos.eq.ha	Hour-angle
Q	pos.eq.ra	Right ascension in equatorial coordinates
Q	pos.eq.spd	South polar distance in equatorial coordinates
S	pos.errorEllipse	Positional error ellipse
P	pos.wcs	WCS keywords
P	pos.wcs.cdmatrix	WCS CDMATRIX
P	pos.wcs.crpix	WCS CRPIX
P	pos.wcs.crval	WCS CRVAL
P	pos.wcs.ctype	WCS CTYPE
P	pos.wcs.naxes	WCS NAXES
P	pos.wcs.naxis	WCS NAXIS
P	pos.wcs.scale	WCS scale or scale of an image

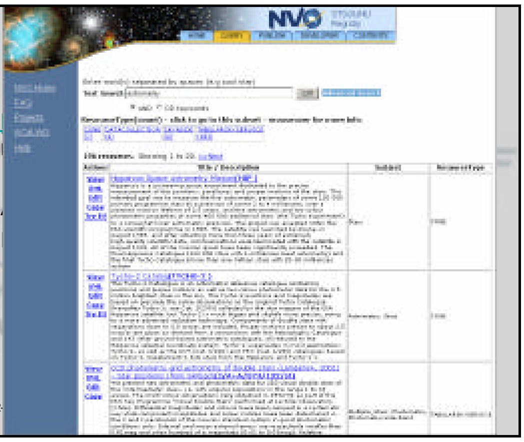
Some UCD's for Position

"P" means that the word can only be used as "primary" or first word;

"S" stands for only secondary: the word cannot be used as the first word to describe a single quantity;

"Q" means that the word can be used indifferently as first or secondary word;


```
<!DOCTYPE VOTABLE SYSTEM "http://us-vo.org/xml/VOTable.dtd ">
<VOTABLE ID="v1.0">
  <DESCRIPTION> SIAP output for Aladin server </DESCRIPTION>
  <RESOURCE type="results">
    <INFO name="QUERY_STATUS" value="OK"/>
      <TABLE>
        <FIELD ID="Observation_Name" ucd="VOX:Image_Title" datatype="char" arraysize ="*" />
        <FIELD ID="CentralPoint_RA" ucd ="POS_EQ_RA_MAIN" datatype ="double" />
        <FIELD ID="CentralPoint_DEC " ucd="POS_EQ_DEC_MAIN" datatype ="double" />
        <FIELD ID="Naxes " ucd="VOX:Image_Naxes" datatype ="int" />
        <FIELD ID="Naxis" ucd ="VOX:Image_Naxis" datatype="int" arraysize ="*" />
        <FIELD ID="AngularPixelSize" ucd="VOX:Image_Scale" datatype ="double" arraysize="*" unit="deg" />
        <FIELD ID="OriginalCoding " ucd="VOX:Image_Format" datatype ="char" arraysize="*" />
        <FIELD ID="FilterName" ucd="VOX:BandPass_ID" datatype="char" arraysize="*" />
        <FIELD ID="Location" ucd="VOX:Image_AccessReference" datatype ="char" arraysize="*" ref="Packaging" />
        <FIELD ID="PlateNumber" datatype="char" arraysize ="*" />
        <FIELD ID="ObservingProgramName" datatype="char" arraysize="*" />
        <DATA>
          <TABLEDATA>
            <TR>
             <TD>GOODS-WFI_ICLWP_DEEP2C-FI</TD>
             <TD>53.119485 </TD>
             <TD>-27.803630 </TD>
             <TD>2</TD>
             <TD></TD>
             <TD>0.000066 0.000066</TD>
             <TD>image/fits</TD>
             <TD>ICLWP</TD>
             <TD>><![CDATA[http://aladin.u -strasbg.fr/cgi-bin/nph -HTTP.cgi?out=image&position=53.054080+ -
27.707217&survey= GOODS-WFI &color=ICLWP field=DEEP2C-FI-PREVIEW&mode=view]]></TD>
             <TD>DEEP2C-FI</TD>
             <TD>GOODS-WFI</TD>
            </TR>
     </TABLEDATA></DATA>
</TABLE>
```



Astrolabe -> Astrometry

Exercise 1
Astrometric Projections

Go to Marc Calabretta's WEBsite and download the images for TAN, STG and SIN. Inspect the FITS header information for each of these images and see the result in SkyCat.

Explain the changes you see while blinking from one to the other.

URL http://www.atnf.csiro.au/people/mcalabre/

Exercise 2
WCS and pixel conversion

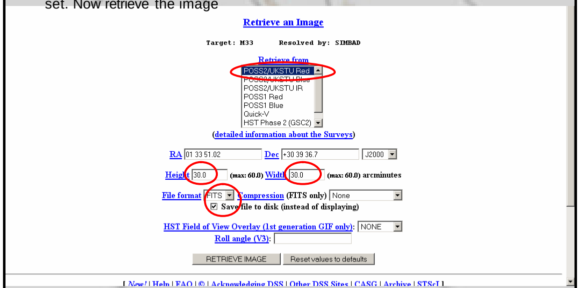
Download the DSS image for M33 (30x30 arcmin) (POSS Red plate).

Enter M33 in the Object Name field and GET COORDINATES. You will now see the bulge center coordinates of M33 in the RA and Dec field.

URL http://archive.stsci.edu/cgi-bin/dss_form

Set the image size to 30 arc minutes in both right ascension and declination.

Select the image source you wish to extract from: POSS2 Red plates. Make sure the file format is set to Fits and the Save to disk checkbox is set. Now retrieve the image



Inspect the image in SkyCat and overlay the image with the USNO catalog.

Explain the coincidence between the USNO catalog entries and some of the stellar object in the image.

Do the same for the Blue POSS plate. Is there any difference?

Inspect the FITS header and describe the difference from the standard WCS description.

Calculate the shift in RA and DEC to extract the DSS image for M33, now not centered on the bulge of M33 but exactly 200 pixels, in each direction, to the North East. Retrieve this Blue POSS image and inspect the correctness of the astrometry and compare both headers.

Now read into IRAF both the M33 bulge centered and 200 pixel offset images. Shift the 200 pixel offset image back to the bulge (just by pixel shifting) and subtract one image from the other. What do you see and why is that.

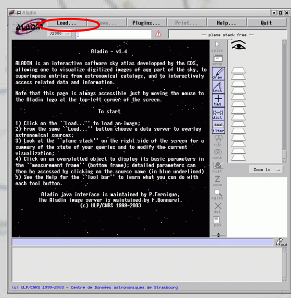
Exercise 3
The time dimension

Example: the binary star **WNO7.

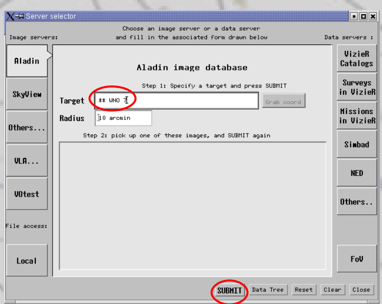
How to visualize the proper motion of stars with Aladin

Tutorial exercise from CDS (Aladin Science Cases)

- Start Aladin (either at http://aladin.u-strasbg.fr/java/nph-aladin.pl?-rm=14.1&-server=Aladin or with the standalone software installed on your machine)
- Click on the **Load** button

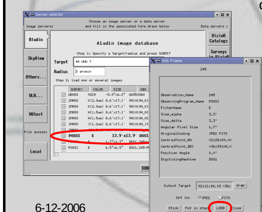


- Type ** WNO 7 in the **target** box
- Click on **SUBMIT**

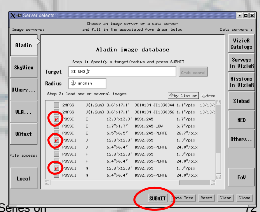


- You have now a list of all the available images around **WNO7
- Choose 3 different plates:
  - DSS1_POSSI_245_E
  - DSS2_POSSII_355_J
  - DSS2_POSSII_355_N

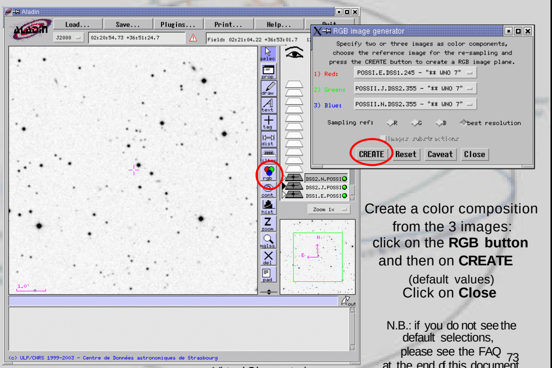
To load an image, **click on the name** of the image and press **Load** or **check the box** on the left and then **SUBMIT.** To close the window, press **Close.**



or



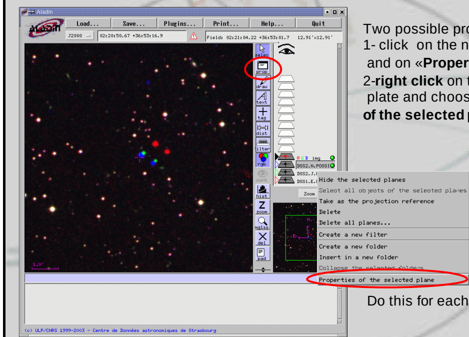
•You get the image display with the 3 images (colour spot flashes until the images are loaded).



Create a color composition from the 3 images: click on the **RGB button** and then on **CREATE** (default values) Click on **Close**

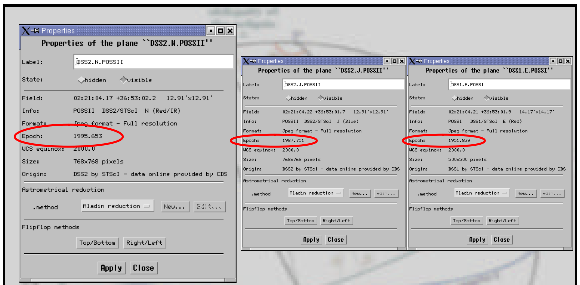
N.B.: if you do not see the default selections, please see the FAQ at the end of this document

You clearly see the position of the binary is different from one plate to another. We are going to quantify this effect.



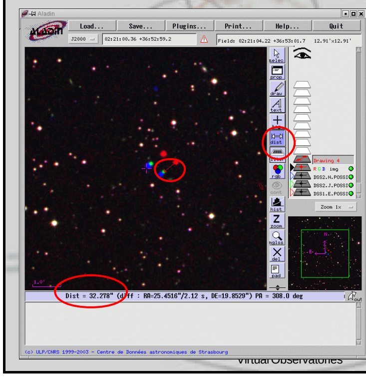
Two possible procedures:
1- click on the name of the plate and on «**Properties** » button; or
2-**right click** on the name of the plate and choose « **Properties of the selected plate** ».

Do this for each of the 3 plates.



For each plate, the corresponding **epoch** appears in the property window:
Band E: 1951.839
Band J: 1987.751
Band N: 1995.653

To measure the distance between two epoch positions: use the **distance button** and drag a double arrow with the left button of your mouse between the 2 points.



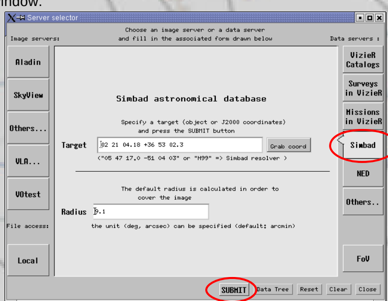
Estimation of the proper motion of ** WNO7:
32 .278''/(1987.751-1951.839)
=0.9''/an

You can delete the arrow by clicking on the **name of the Drawing plate** and press **del**

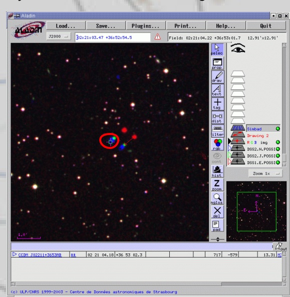
N.B.: if you do not see the distance indication, please refer to the FAQ

You can go further…

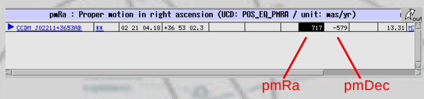
•You can compare this value to estimations from the litterature via the Simbad databas
•Click on **Load**
•Click on the **Simbad** tab on the right
•Click on **SUBMIT**
•**Close** the window.



A new plane is downloaded. It contains the Simbad objects for this region.
Two squares appear near each of the stars of the binary.
Each of it is an object in Simbad
•**Clik on a square**
•Below the image, you can see a line containing the information on the object selecte



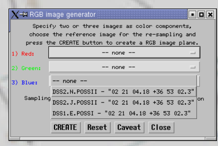
By moving your mouse over the different boxes contained in the line, you see the associated labels.



Proper motion in Simbad: 0.9 ''/yr
It is consistent with our simple estimation

FAQ

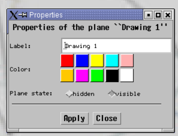
- When I press the RGB button, I don't have the proper images selected by default. Why?
  - This can happen if you loaded other images before. You then have to select them manually in the scrolling list.



- I used to plot a double arrow with the « dist » button, but I don't see the distance indication line
  - Your mouse has to be positioned on the arrow to see the information line
  - If you have selected a different plane after the drawing, your distance indicator is lost. You will have to redraw a double arrow in a new plane.

FAQ (2)

- How do I change the colours of the symbols or drawings?
  - Clic on the name of the plane you want to modify
  - Push the **Prop** button (properties)
  - Select the colour that suits you
  - Press **Apply** and **Close**



Exercise 4 (Optional)

Astrometric calibration with Aladin

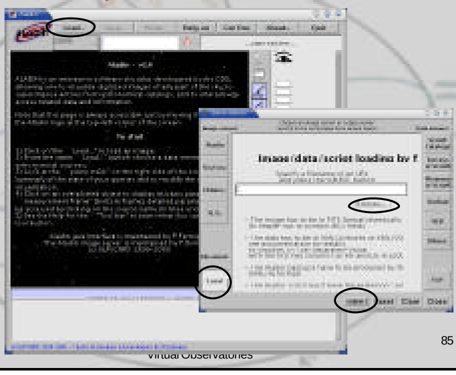
Tutorial exercise from CDS (Aladin Science Cases)

How to calibrate the astrometry of an uncalibrated image: step by step

- Install the Aladin standalone version
- Load your local image
- *1st solution*: use of an astrometrically calibrated image (DSS)
- *2nd solution*: use of an astrometrically calibrated point source catalogue (2MASS)
- load the DSS image/ 2MASS catalogue
- Calibrate crudely your image with the DSS image
- **1st solution**: plot the point sources onto your image
- Identify and enter image positions and corresponding point source positions
- **2nd solution**: create your own point source catalogue in identifying and entering point sources on the DSS image
- Plot the point sources onto your image
- Identify and enter image positions and corresponding point source positions
- Save the calibrated image

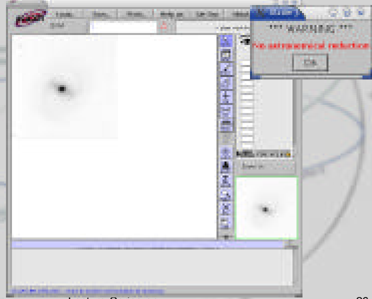
In order to work with your *own local files*, you have to install the *standalone* version of Aladin from the web. (http://aladin.u-strasbg.fr/AladinJava?frame=downloading)

In order to load your FITS file into Aladin click on 'Load'. A new window pops up. Click on 'Local' and 'Browse' your local file system. When you have found your file click on 'SUBMIT'.

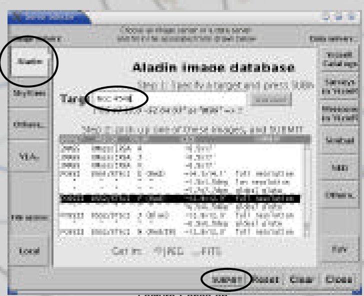


The image appears in the Aladin window together with a warning that there is no astrometry associated with the FITS file.
We have chosen an H band image provided by Gavazzi et al.*

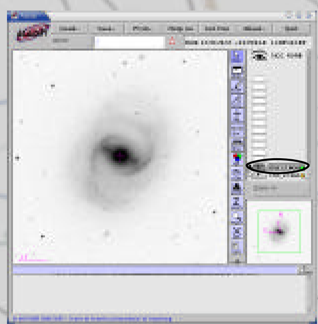
*) The image has been downloaded from the GOLDMine database, which is operated by the University of Milano-Bicocca (see 2002, A&A, 400, 451).



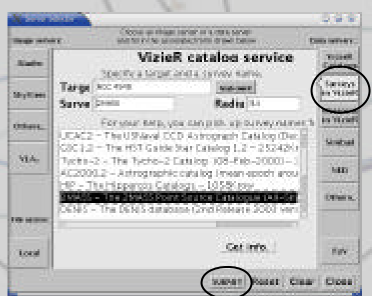
In order to load a DSS image that is astrometricallycalibrated, click on 'Aladin', type the target name, chose the image you want to display and click on 'SUBMIT'.



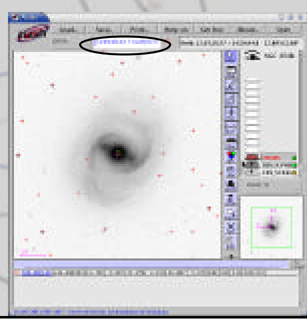
The DSS image is loaded in a second plane and appears in the Aladin window.



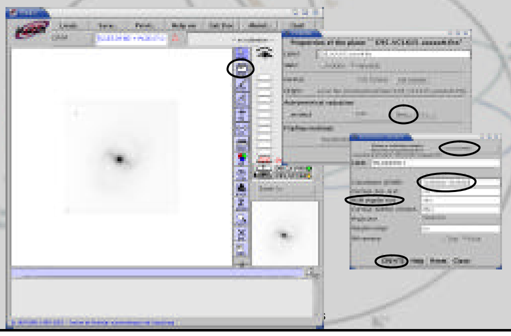
1st solution: use of an astrometrically calibrated image.
Chose a reference catalogue as close as possible to your image wavelength (e.g. 2MASS). To load the point source catalogue for the astrometric calibration, click on 'Surveys in VizieR', chose the catalogue and click on 'SUBMIT'.



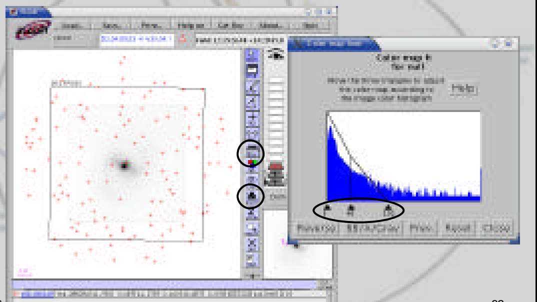
The 2MASS point sources are loaded into a third plane and appear as red crosses on the DSS image. In order to assign first, crude coordinates to the uncalibrated image, click on the center of the galaxy, leave the image with the cursor and grab the coordiantes with the cursor (written in blue).



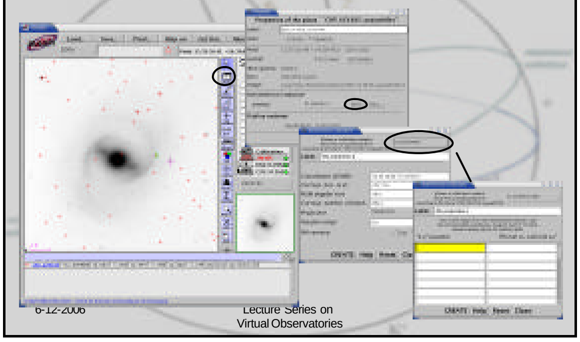
Go back to the uncalibrated image, click on 'prop'. A new window appears. Click on 'New'. Again, a new window appears. Chose 'by parameters'. Paste the grapped coordiantes into the corresponding field. Click on 'CREATE'. Fill in a first guess for the 'angular size' of the field.



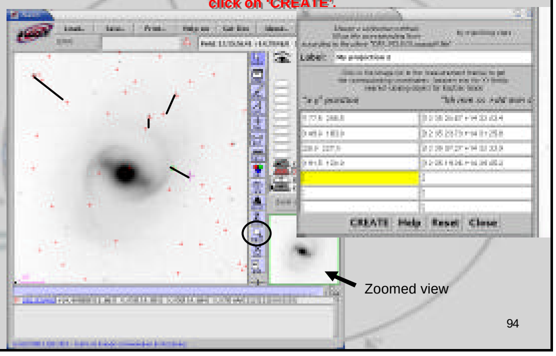
It is only now that you can display the 2MASS sources on the crudely calibrated image. Click on 'pixel' to change the greyscale by dragging the black arrows to the left. For an easier calibration using only the brightes 2MASS sources, a 'filter' (magnitude cut of 15) can be applied.



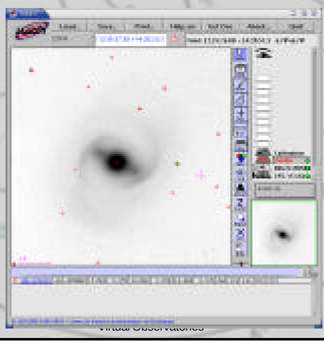
The stars are now better visible. Click on 'prop'. A new window appears. Click on 'New'. Again, a new window appears. Change the upper right panel into 'by matching stars', then click on the sub-window 'x-y position', which then becomes yellow.



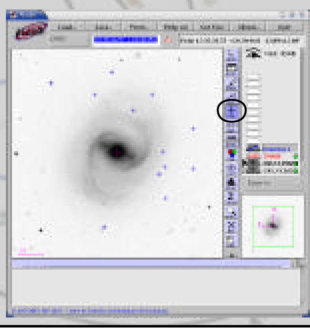
In order to fill in the columns, for each star that you want to use as a reference, click first on its x-y position on the uncalibrated image, then click on the corresponding star of the 2MASS catalogue (red cross). Use 'mglss' to view the zoomed region in the lower right corner of the Aladin main window. At the end click on 'CREATE'.



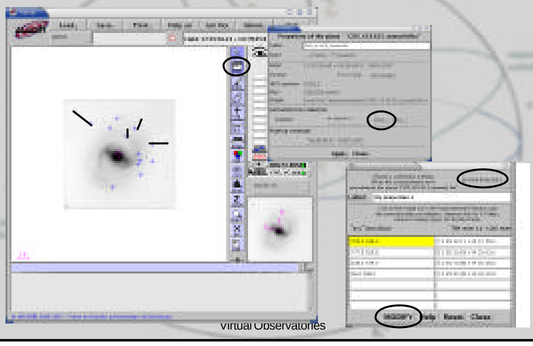
Now the image has a correct astrometry with respect to the 2MASS catalogue, i.e. the 2MASS sources (red crosses) fall onto the stars on the image.



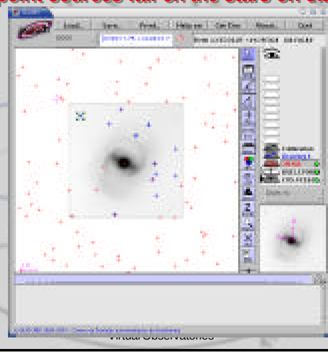
2nd solution: create your own star catalogue using the DSS image. Click on 'tag' and mark the stars on the image.



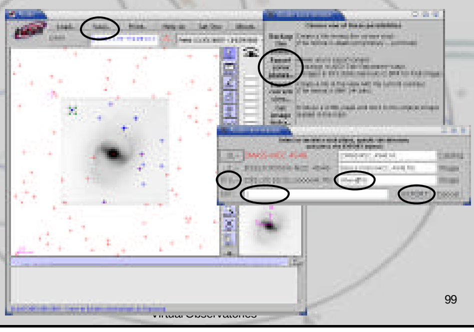
Change to the crudely calibrated image, click on 'prop'. Click on 'New' on the new window. Change the upper right panel into 'by matching stars'. Fill in the columns as before.
Click on 'MODIFY' or 'CREATE'.



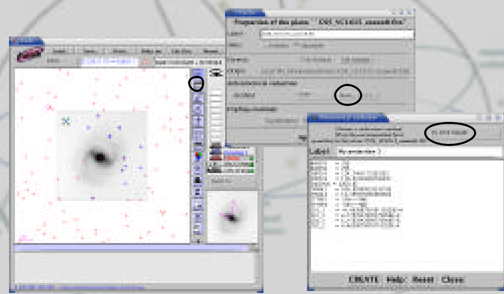
The correct astrometry with respect to the DSS image is now associated with the image. One can now check if the 2MASS point sources fall on the stars on the image.



To save the image click on 'Save'. Click on 'Export some planes' on the new window, chose the newly calibrated image, type the name you want to assign to it into the corresponding field, specify the directory where it will be saved and click on 'EXPORT'.



You can also display and edit the FITS header directly by clicking on 'prop' in the main window and on 'New' on the appearing window. Change the upper right panel in the appearing window into 'by WCS header'.



Precision of the astrometric calibration:

(i) When clicking on the star on an image the program does not yet search for the source centroide. Thus the precision of the astrometry depends on your ability to hit the right position of the star on the image (use 'mglss').

(ii) The calibrated images is written out as a FITS file with 8 bits resolution. If your original image had a higher resolution it will be saved in a degraded resolution.

These items will be improved soon.