Reference Frames & Zonal Errors:

Where do they come from and why do we care about them?

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Reference Systems and Frames

- System: theoretical concept of a system of coordinates including theories, time and standards. Example: ICRS

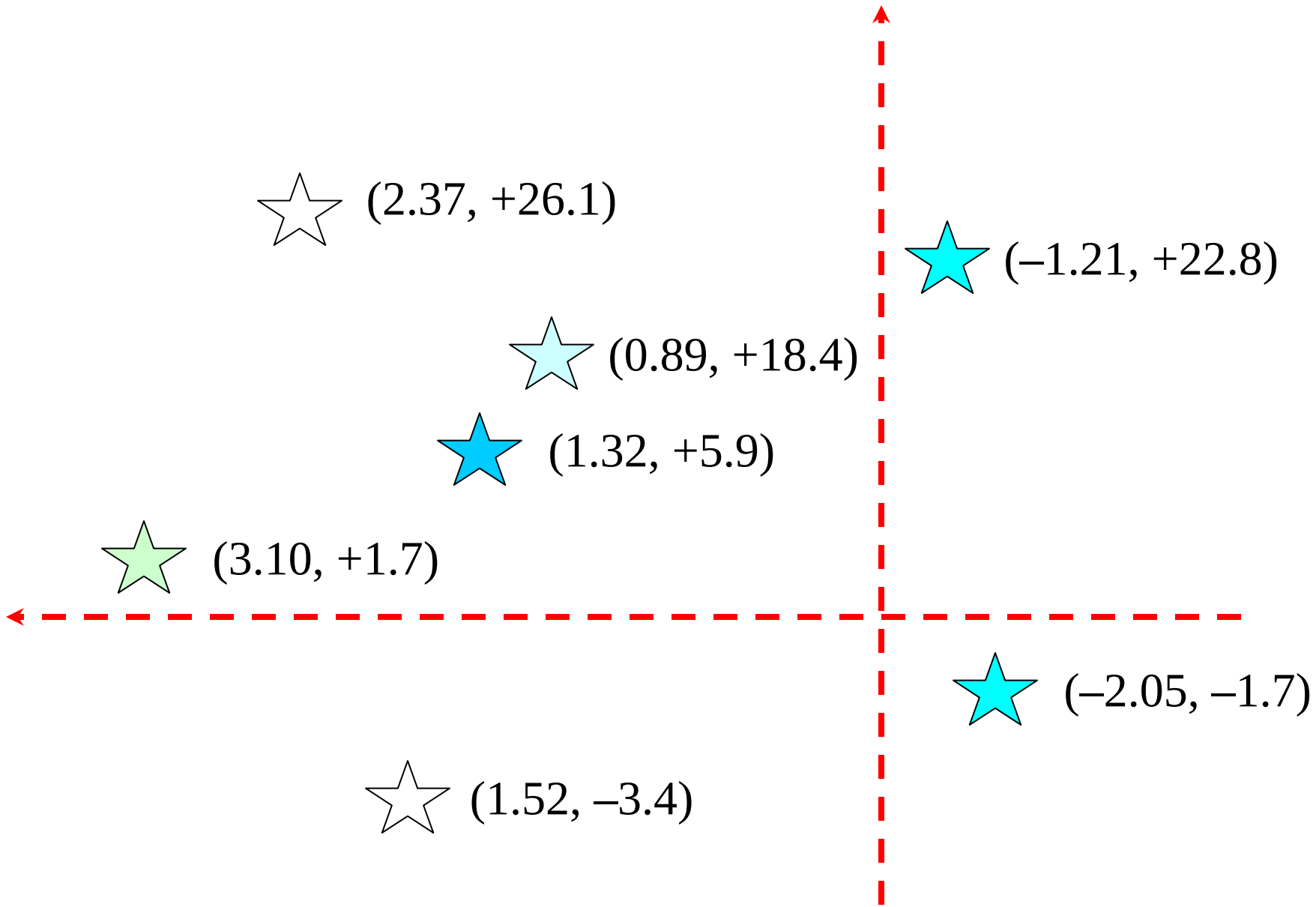
- Frame: practical realization of a reference system, usually as a catalog of positions and proper motions of a certain number of fiducial points on the sky. Example: ICRF

What is an Astronomical Reference Frame?

An ensemble of coordinate values (and their rates of change) assigned to specific astronomical objects for a given epoch

For example, the data in a star catalog

This is completely analogous to the establishment of a geodetic reference system using an ensemble of Earth-fixed benchmarks whose coordinates are have been determined


(2.37, +26.1)
(–1.21, +22.8)
(0.89, +18.4)
(1.32, +5.9)
(3.10, +1.7)
(–2.05, –1.7)
(1.52, –3.4)

Types of Astronomical Reference Frames

- Extragalactic

  Fiducial points are quasars or nuclei of galaxies

  - Constructed from radio λ observations (VLBI)
  - No assumed angular motions — too far away
  - But …radio sources often variable

- Galactic (Stellar)

  Fiducial points are stars

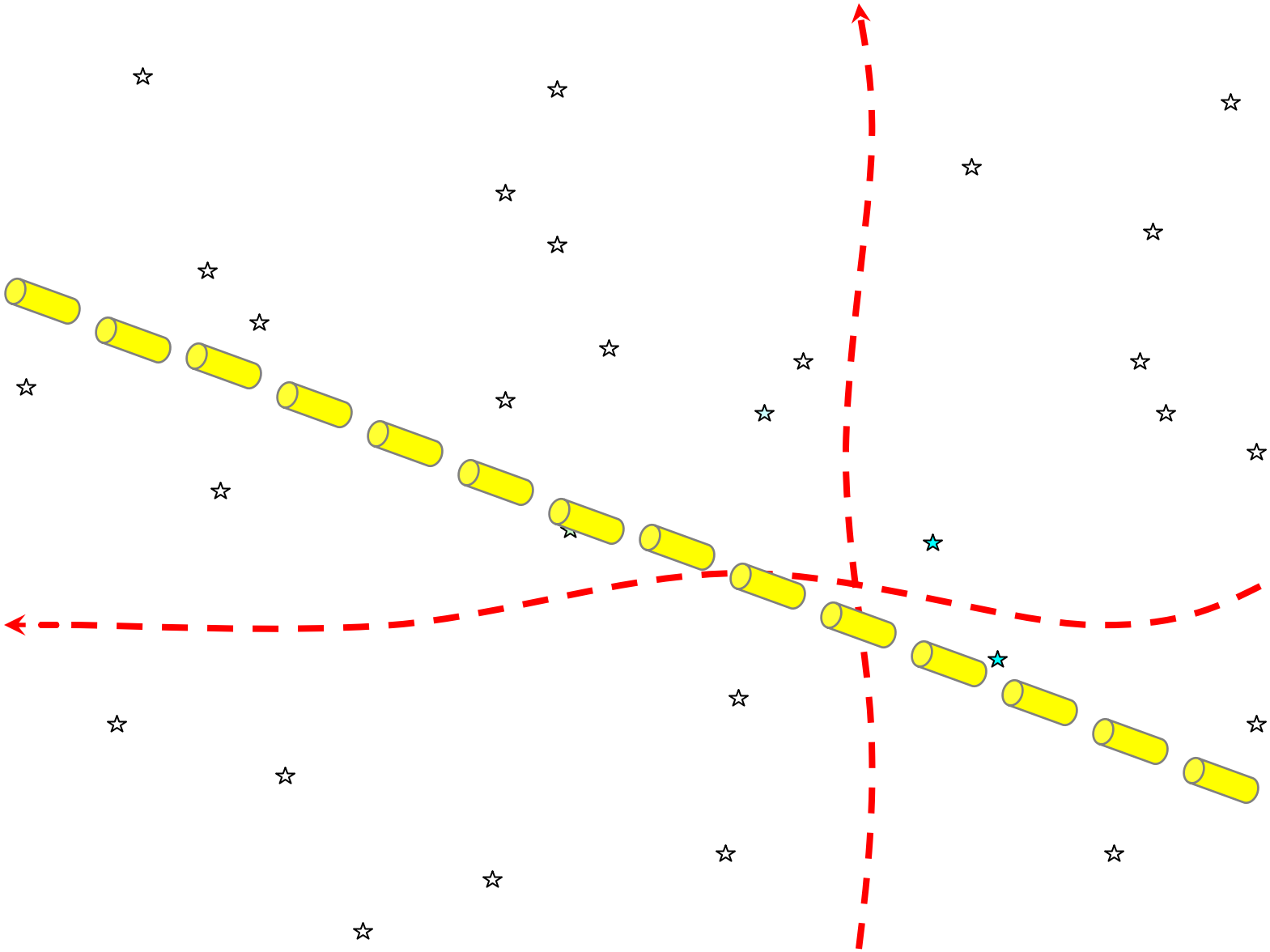
  - Lots of energy
  - Energy in λ bands of practical use
  - But … stars move, sometimes in complex ways

- Dynamical

  Fiducial points are planets or other orbiting bodies in the solar system (natural or artificial)

Complications

- Problem is over-determined: really only need two stars (3 coordinates) to define a reference frame
- Therefore, for N stars in a catalog, ~$N^2/2$ independent reference frame definitions — which will not, in general, be consistent due to errors in coordinate values
- Not a bad problem as long as errors are random
- If errors are a function of position on the sky, the reference frame is warped (systematic distortions)
- Also problematic if errors are a function of magnitude or color



Desirable Features of Astronomical Reference Frames

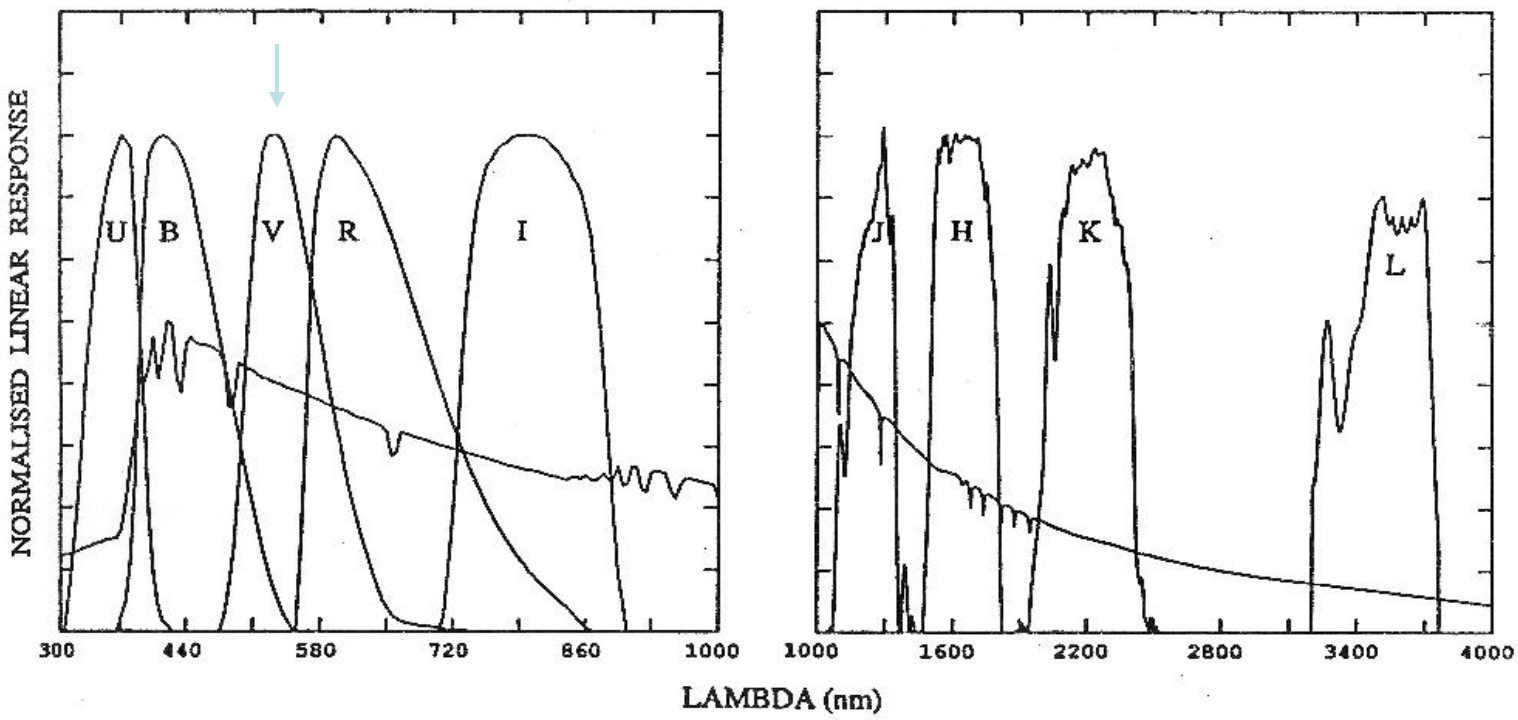
- Should define a local *inertial* reference system

  (no rotations)
- Should be *isotropic* (no distortions)
- Should be *accurate*
- Should have a suitable *density* of fiducial points
- Should have fiducial points *detectable* by relevant sensors (sufficient flux in sensor bandpass)

Issues in Constructing Reference Frames

- Stars part of galaxy, inherently a non-inertial system
- Stars often part of binary or multiple systems
  - If resolved, orbital motions of components must be determined
  - If unresolved, photocenter may move or be $f(\lambda)$
- Parallax (distance) of stars must be determined
- Quasars and AGNs have time-variable flux and structure
- Aligning reference frames from different λ regimes difficult — objects bright in one regime faint in the other

UBVRIJHKL Photometric Bands



The passbands of the *UBVRIJHKL* system, plotted as functions of the wavelength in nm.

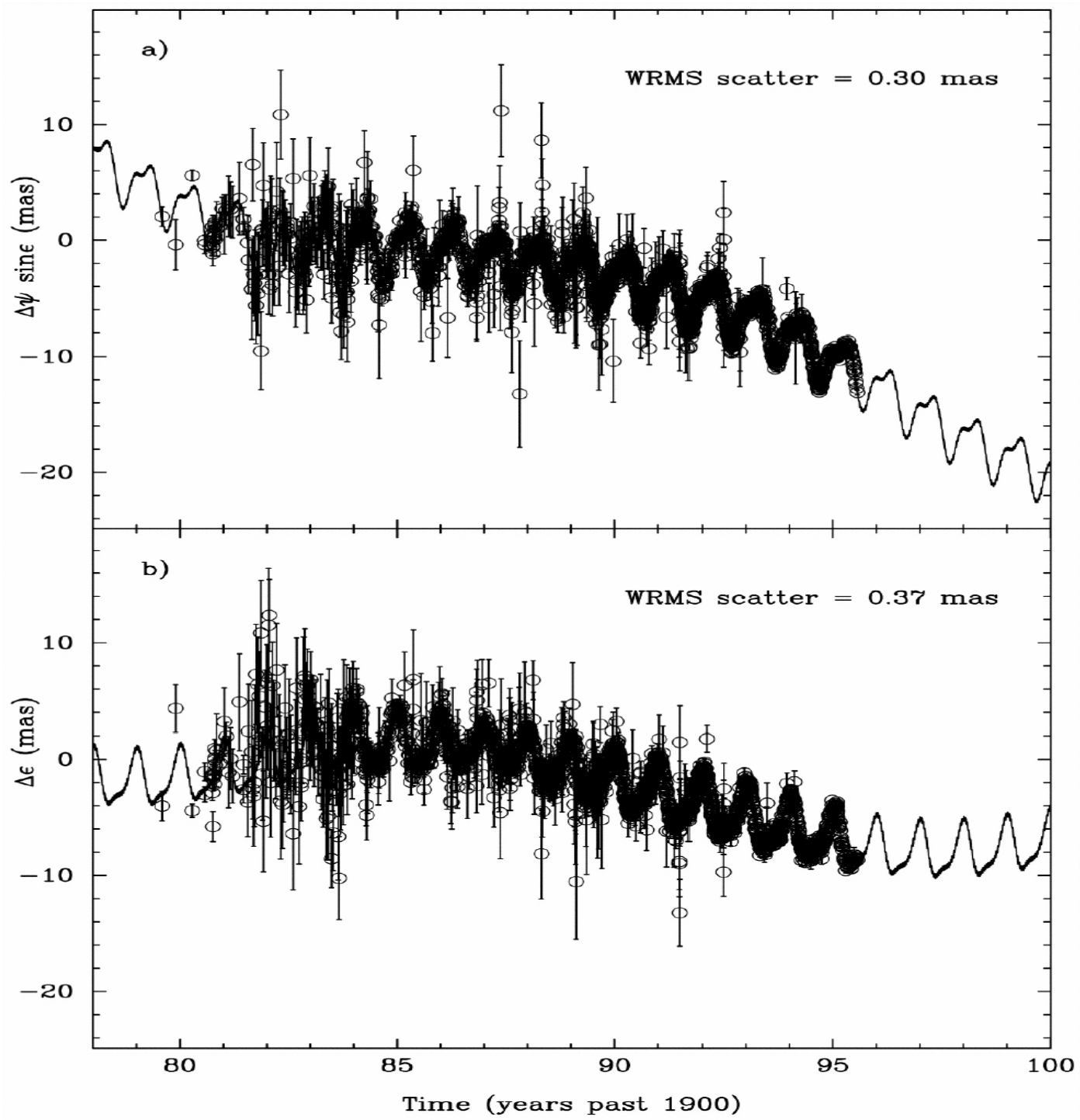
from *The Astronomy and Astrophysics Encyclopedia*, ed. S. P. Maran (1992)

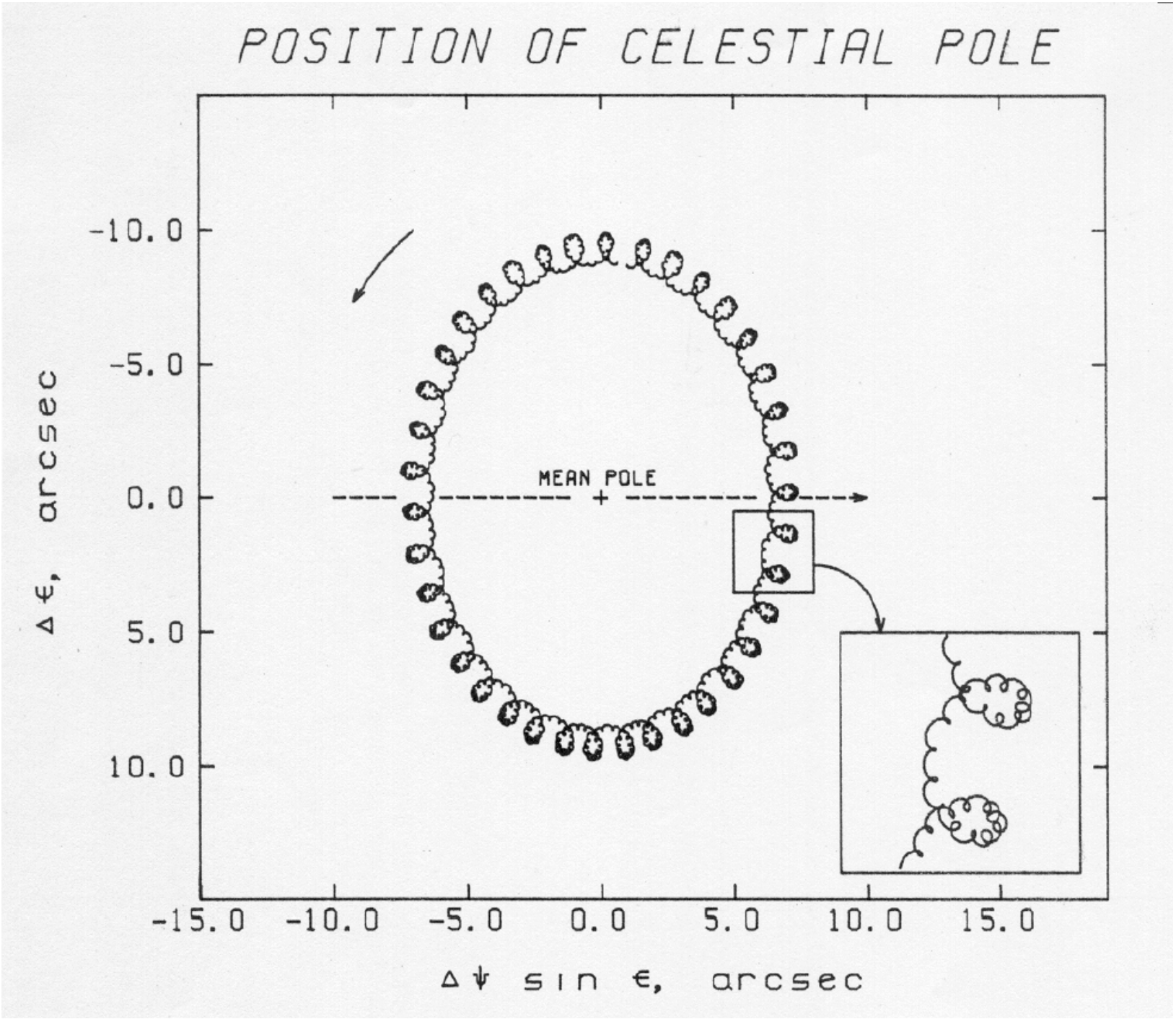
Past Reference Frames

- Solar system based- dynamical equinox
- Ecliptic, equator, equinox
- Nearby bright stars- catalog equinox
- Proper Motions – Double Stars
- Precession and nutation
- Mean equinox of date
- Epoch dependent B1950.0 J2000.0
- Newcomb’s Theory of the Sun- tropical year
- Fundamental Catalogs- FK3, FK4, FK5

Kinematics

- Precession
- Nutation
- Earth Rotation
- Polar Motion


a)
WRMS scatter = 0.30 mas
Δψ sinε (mas)
10
0
−10
−20
b)
WRMS scatter = 0.37 mas
Δε (mas)
10
0
−10
−20
80
85
90
95
100
Time (years past 1900)


POSITION OF CELESTIAL POLE
MEAN POLE
-10.0
-5.0
0.0
5.0
10.0
-15.0
-10.0
-5.0
0.0
5.0
10.0
15.0
Δε, arcsec
Δψ sin ε, arcsec

International Celestial Reference System (ICRS)

- extragalactic radio sources
- fixed reference frame
- Epoch independent
- Kinematically based-Earth motions
- relativistic definitions
- Barycentric Celestial Reference System
- Geocentric Celestial Reference System
- Independent of solar system
- Arbitrary orientation
- Close to J2000.0 dynamical system

Implementations

- International Celestial Reference Frame ~ 0.2 mas
  - extragalactic radio sources
  - very distant, not moving
  - possible structure variations
  - optically faint
- Hipparcos Catalog ~ 1 mas
  - optical to 11 mag, 118000 stars
  - stars without problems
- Tycho 2 Catalog ~ 20 mas
  - densifies Hipparcos, 11 mag
- UCAC ~ 30 - 70 mas
  - 16 mag
  - 50,000,000+ stars
- USNO B2 ~ 200 mas
  - 21 mag
  - billions of stars
- Remember stars still have proper motions

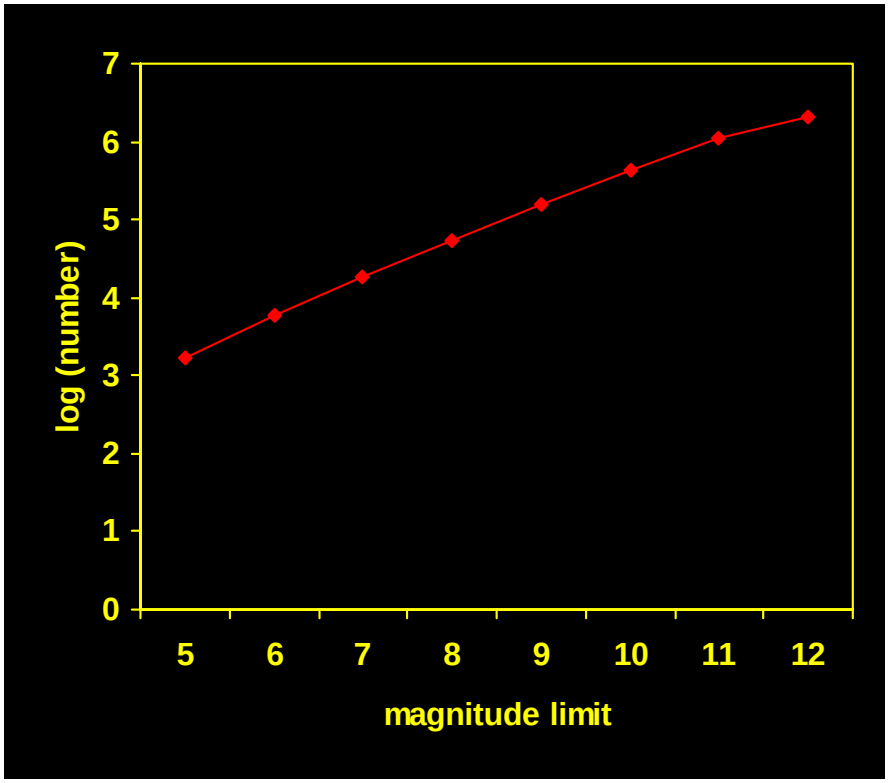
Scale of Visual Magnitude

–4	Venus
–1.5	Sirius
0 to 6	most naked-eye stars
5	Andromeda galaxy
~8	magnitude at which there is 1 star / degree^2
9-10	faintest stars in binoculars
12	faintest stars in small (3-inch) telescope
12	brightest quasar (most are 15 and fainter)
14	Pluto
19.5	Palomar Sky Survey V limit
~24	old photo plate limit with 200” telescope
29	current limit?

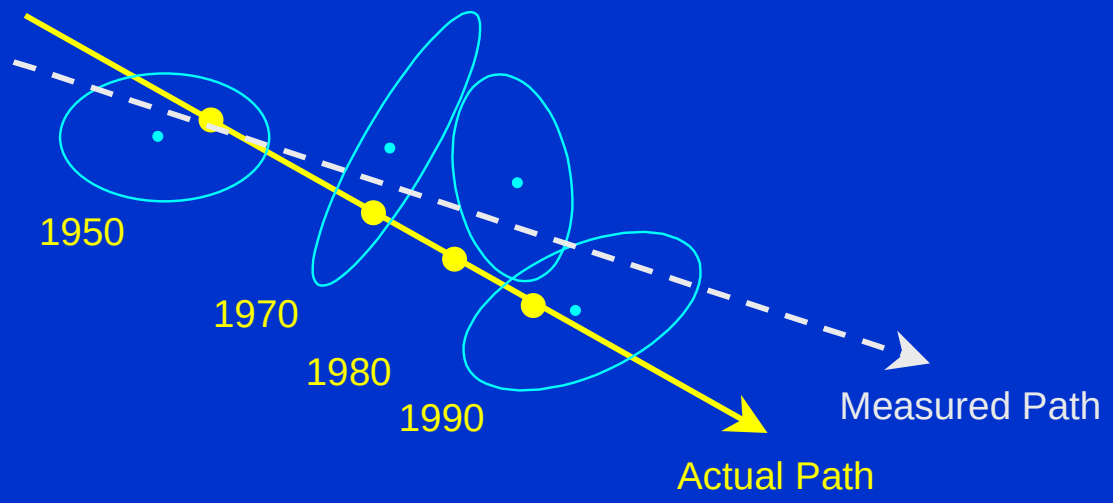
Star Numbers vs. Magnitude

Star Counts from Tycho-2

m_V limit	no. stars
5.0	1,658
6.0	5,713
7.0	18,183
8.0	54,192
9.0	154,656
10.0	417,769
11.0	1,083,253
12.0	2,158,589



Why star positions, and the reference frames they define, degrade with time

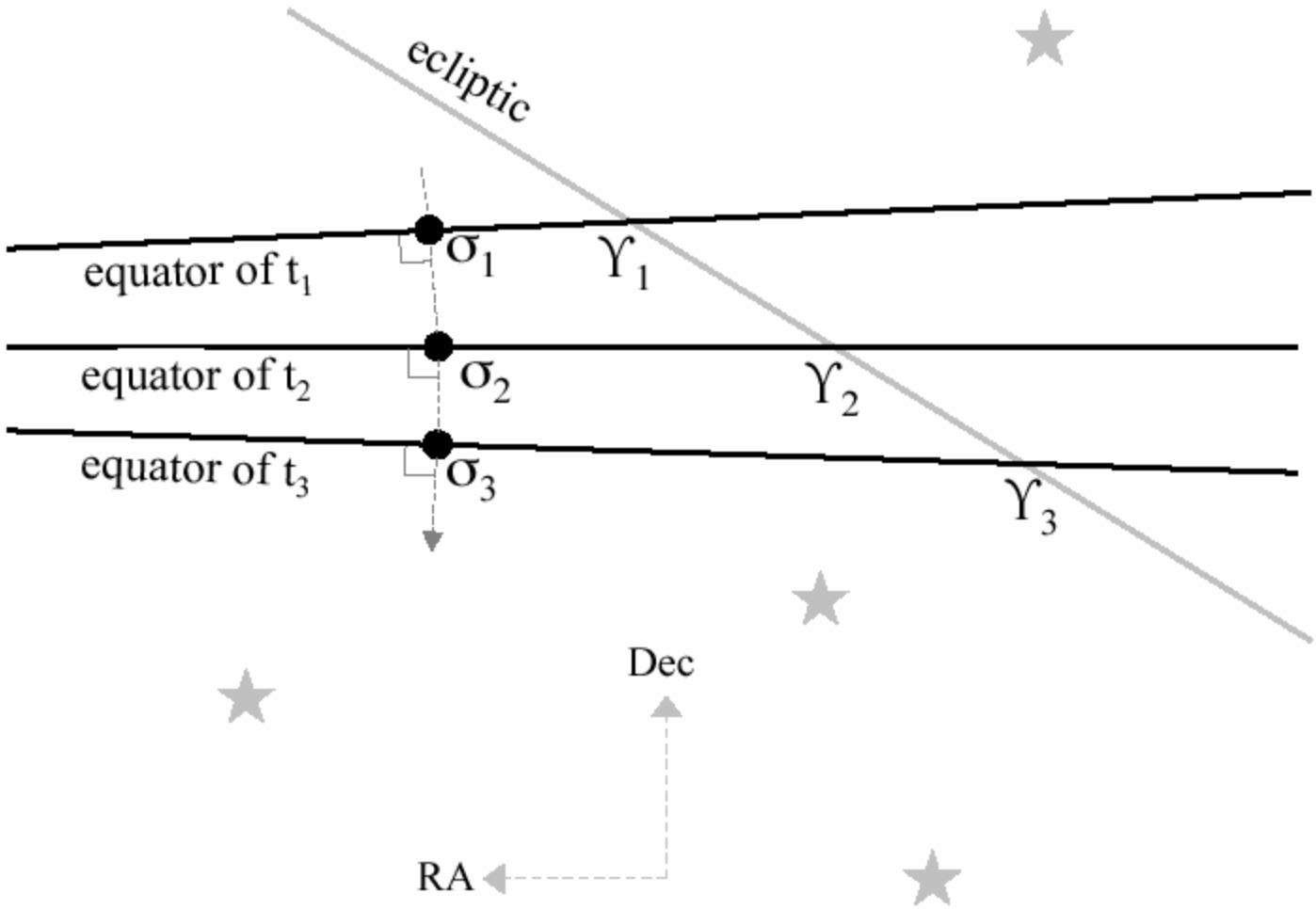


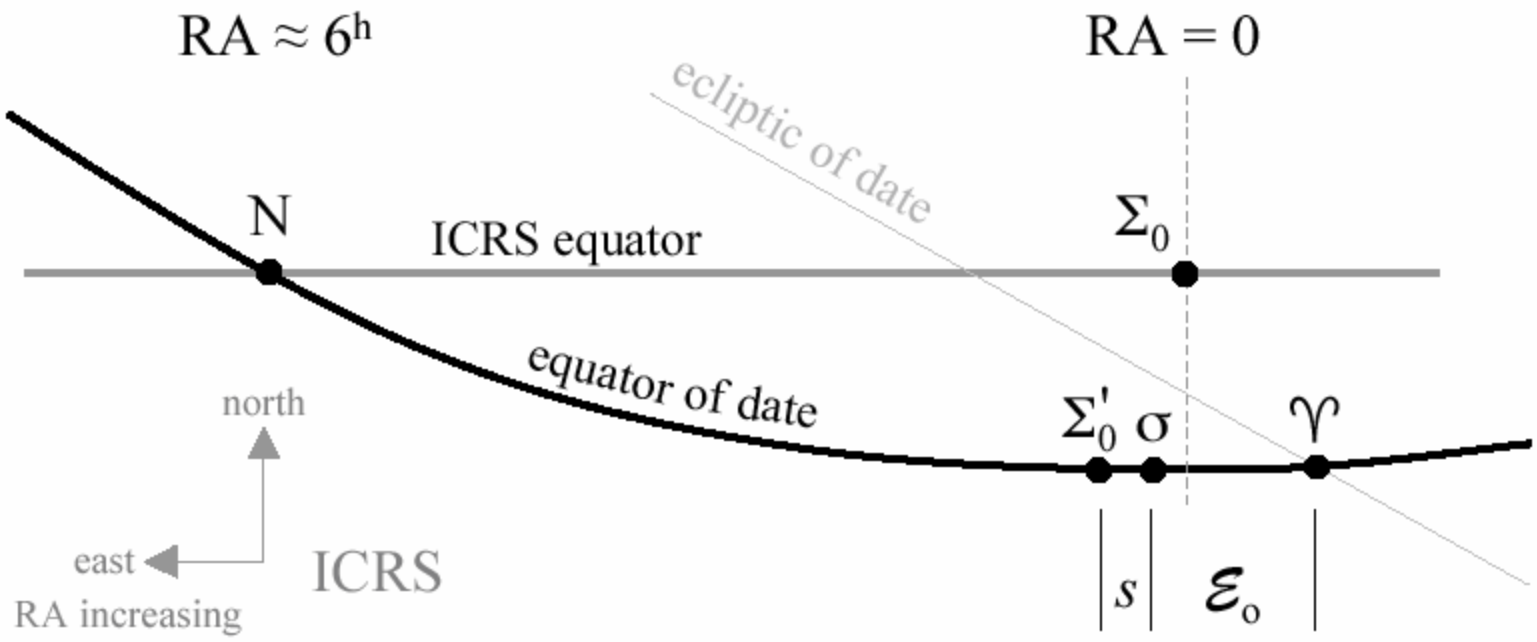
Moving Reference systems - Proposed changes

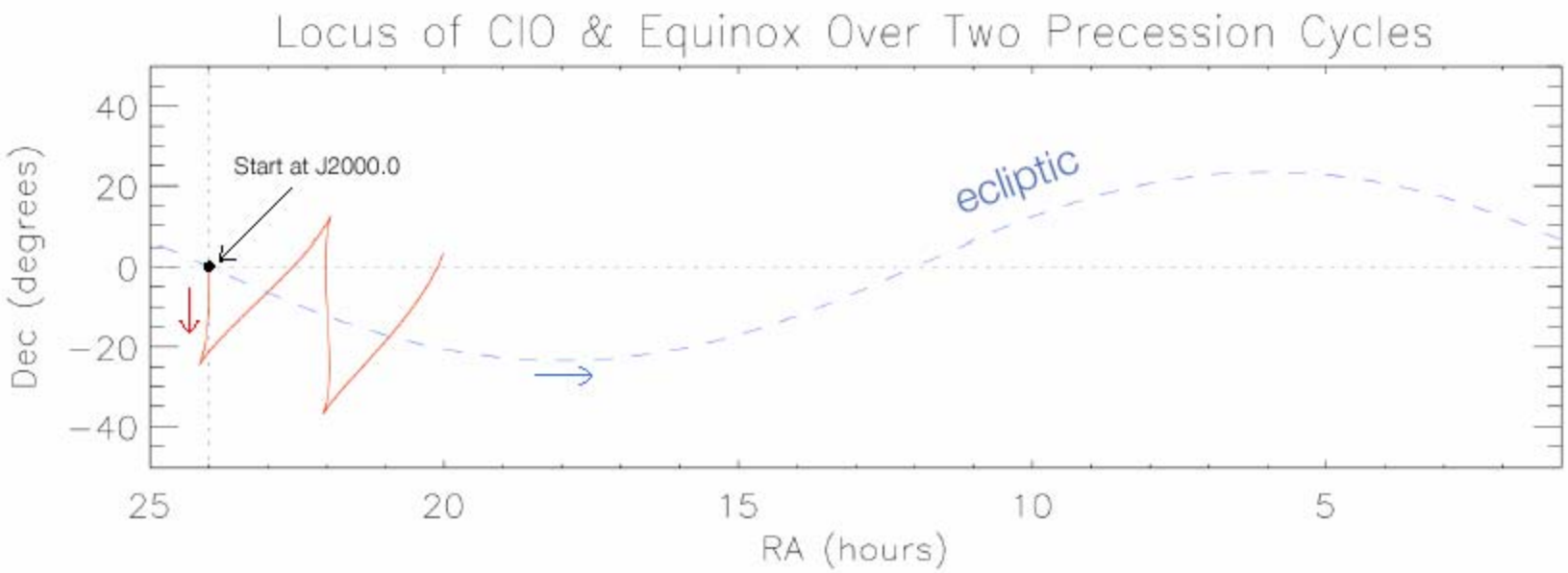
- Earth kinematics instead of Solar system dynamics
- New precession-nutation model - IAU 2000A
- New pole - Celestial Intermediate Pole (CIP)
  - determined from IAU 2000A
- New fiducial point - based on non rotating origin
  - no motion along instantaneous equator
  - all motion is perpendicular to instantaneous equator
  - Celestial Intermediate Origin (CIO)
  - replaces equinox

Moving Reference systems - Proposed changes (cont)

- Earth Rotation Angle (ERA)
  - replaces sidereal time or GAST
- Terrestrial Intermediate Origin (TIO)
  - based on International Terrestrial Reference System (ITRS) of IUGG
- International Terrestrial Reference Frame (ITRF) - catalog of Earth points
- Intermediate Reference System (IRS)
  - CIP based
- sub daily periodic terms determined from GPS data
  - Nutation terms > 2 day periods
  - So polar motion includes all terms < 2 day periods
- Geodesic precession and nutation in precession-nutation model


ecliptic
equator of t_1
equator of t_2
equator of t_3
σ_1
σ_2
σ_3
Υ_1
Υ_2
Υ_3
Dec
RA


RA ≈ 6h
RA = 0
ecliptic of date
N
ICRS equator
Σ0
equator of date
Σ'0
σ
ϒ
north
east
RA increasing
ICRS
s
ε0


Locus of CIO & Equinox Over Two Precession Cycles
Start at J2000.0
ecliptic
Dec (degrees)
40
20
0
−20
−40
25
20
15
10
5
RA (hours)

Implementation Possibilities

- New Precession Theory
  - Goes with IAU 2000A precession - nutation model
  - Establishes accurate equinox based system
- For best accuracy, use CIO, TIO, Earth Rotation Angle(ERA)
  - Earth Orientation Community does this
- For many applications, use equinox based system
  - use equinox, precession theory, IAU 2000A nutation
  - sidereal time from ERA
- IERS and Almanac Offices provide data for both systems
- Need for education of scientists on these systems

International Terrestrial Reference Frame (ITRF)

- Defined by stations on Earth
- No global rotation-continental drifts
- Terrestrial Intermediate Origin
- Not quite Greenwich
- Continental Drift

Earth Orientation

- VLBI Observations- extragalactic sources
- Lunar Laser Ranging
- Global Positioning System observations-not independent
- Predictions from theories and data fitting
- International Earth Rotation and Reference System Service

Transformation

- ICRF = PN(t) x R(t) x W (t) x ITRF
- Be careful of : celestial pole offsets
- equinox offset - definition dependent

Time Scales

- International Atomic Time (TAI) from physics
- Universal Time (UT1) Earth rotation time
- Terrestrial Time (TT) ideal time for Earth
  - TT = TAI + 32.184 s one realization
  - Delta T = TT - UT
  - replaces TDT
- Universal Time Coordinated (UTC)
  - UTC - UT < +/- 0.9
  - UTC = TAI - N seconds (now 32 s)

Time Scales

- Geocentric Coordinate Time (GCT)
  - TCG - TT = Lg x (JD- 2443144.5) x 86400s
  - Lg is a defining constant
- Barycentric Coordinate Time (BCT)
  - TCB - TCG = secular and periodic terms
- Barycentric Dynamical Time (TDB)
  - TDB - TT = periodic terms only - old definition
  - Linear function of TCB – ephemeris dependent
- Teph Time scale of JPL ephemerides
  - a rescaled time scale to have the same rate as TT
  - Also called TDB
- UTC Redefinition ?

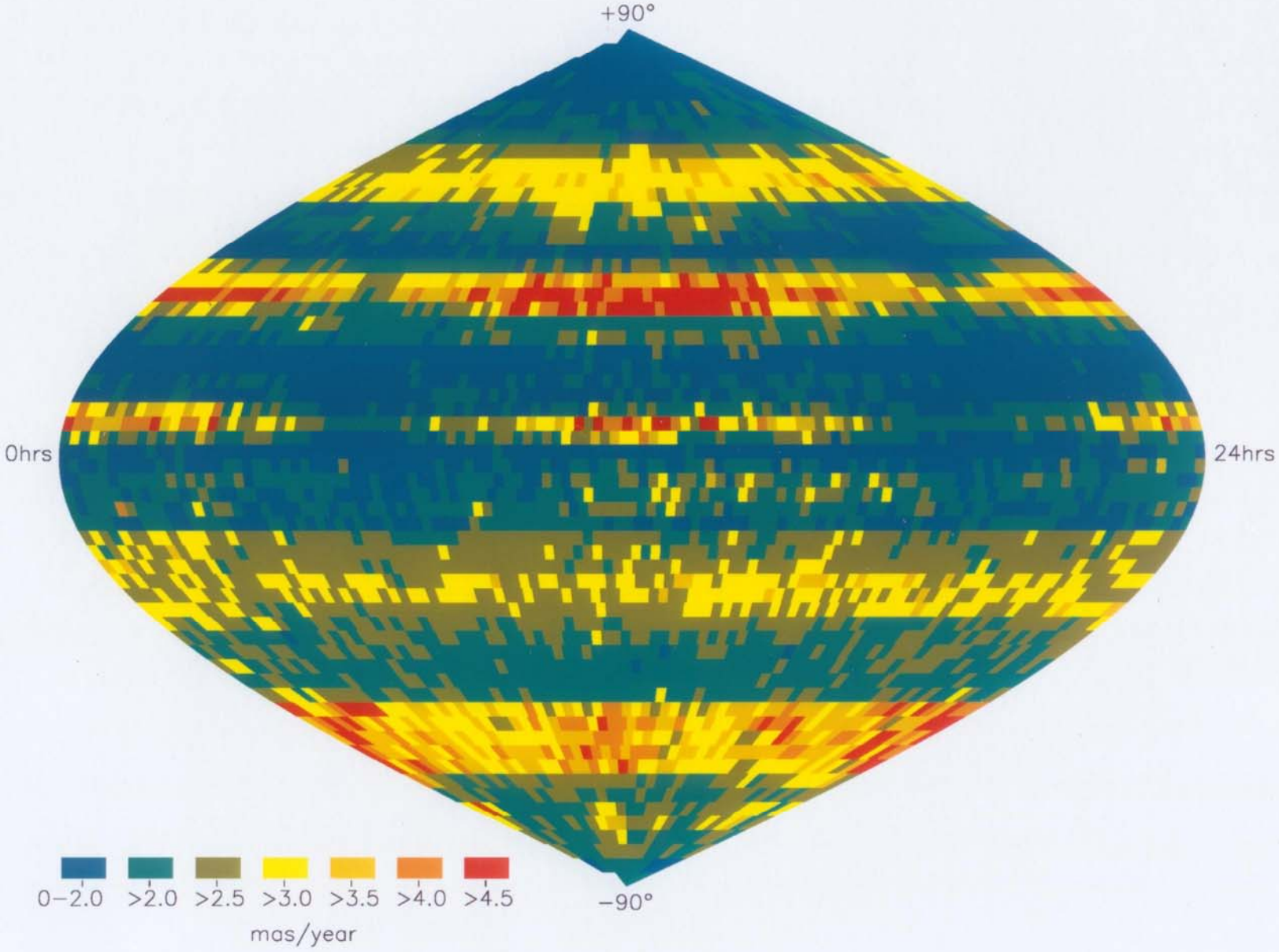
Observational Errors

- Refraction Effects-altitude dependent-declination errors
- Optical distortions
- Declination zones from observatories
- Reference star errors-parallaxes and proper motions
- Measuring machine, detector systematics
- Centroiding errors
- Reference star distributions
- Errors as functions of separation

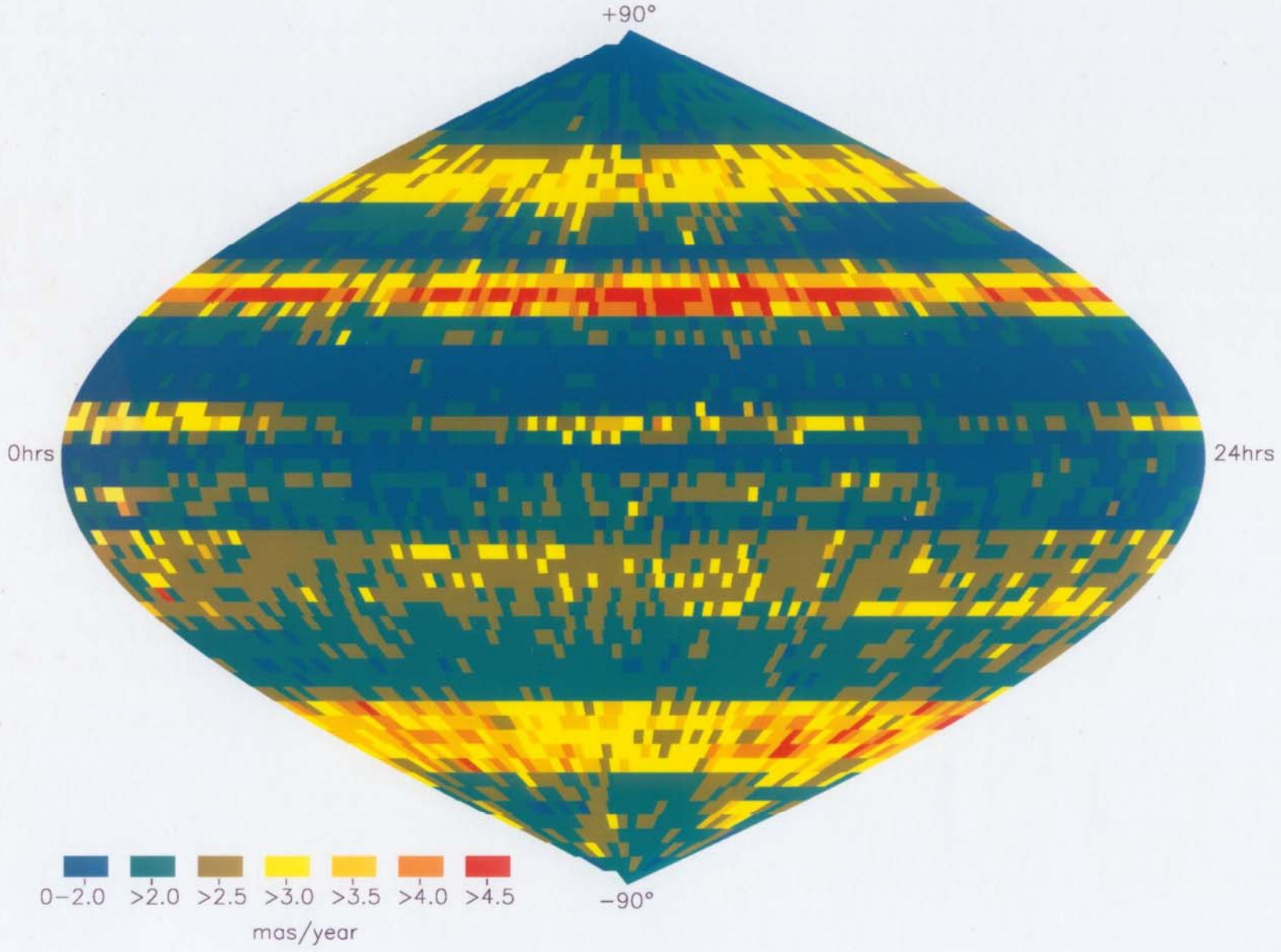
Zonal Errors

- Declinations
- Plate center distance
- Instrument and measuring technique
- Observatories and Instruments
- Reduction methods

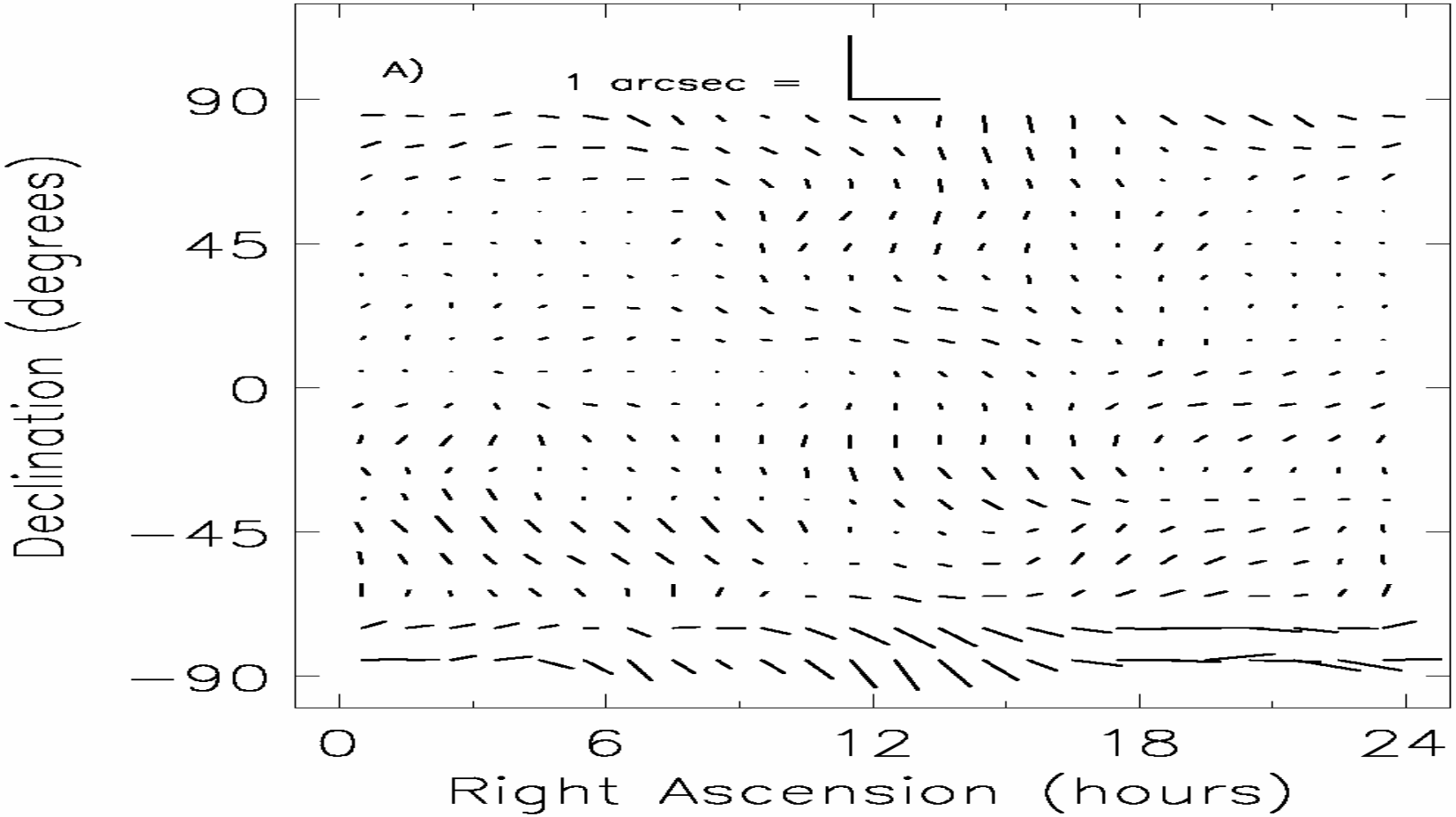
ACT MEAN σ PM (RA)



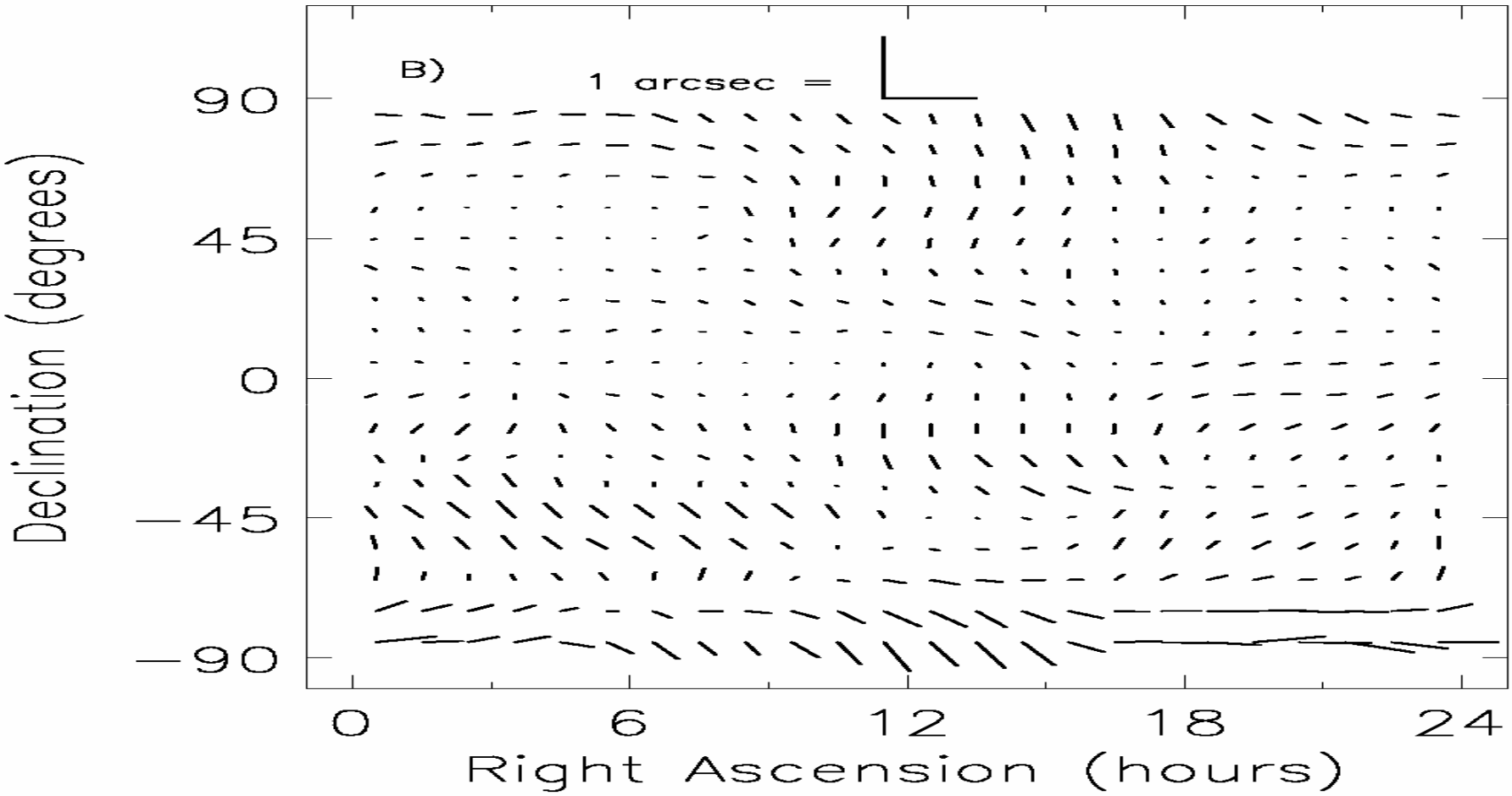
ACT MEAN σ PM (DEC)



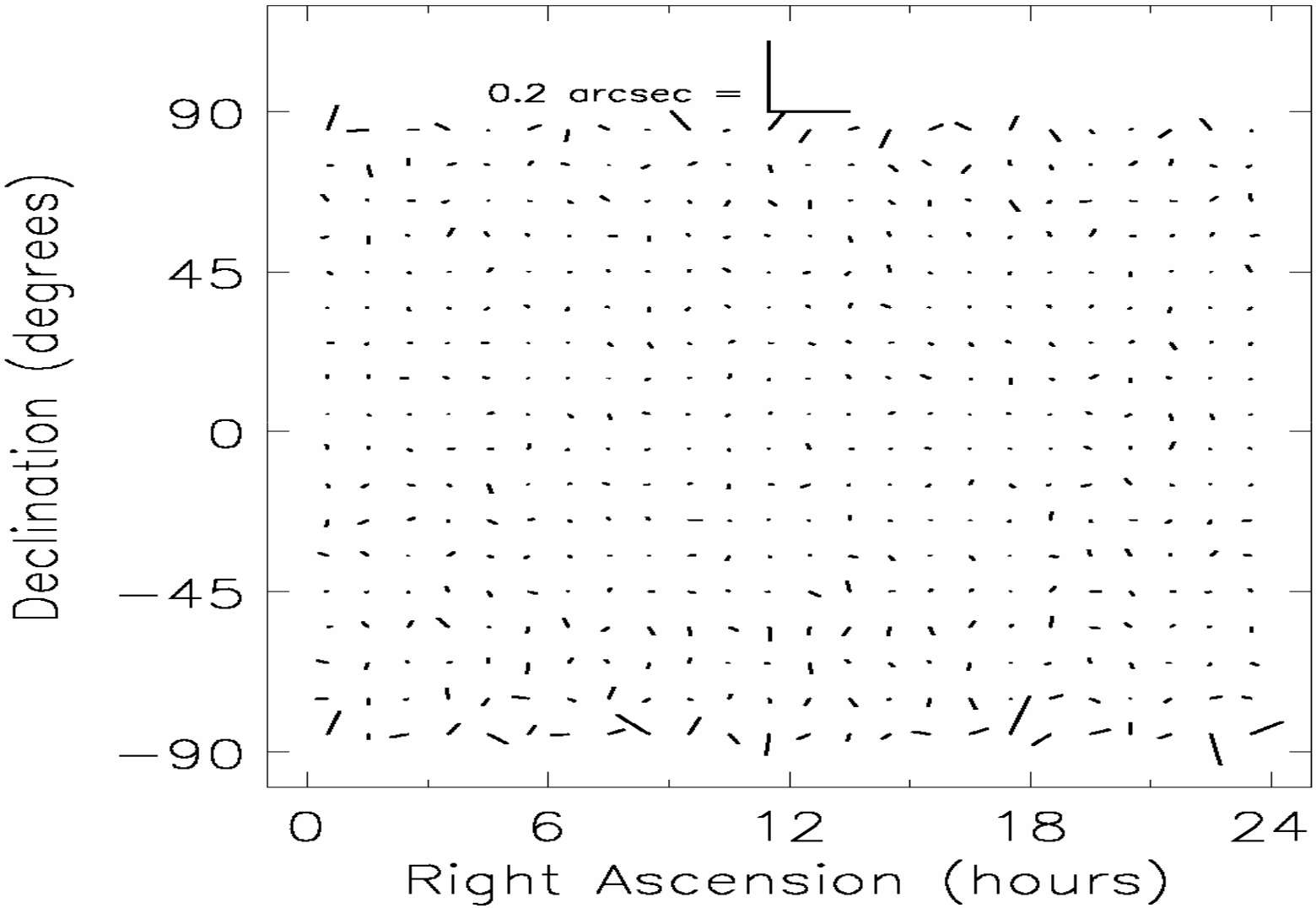
AC on FK5 and Hipparcos

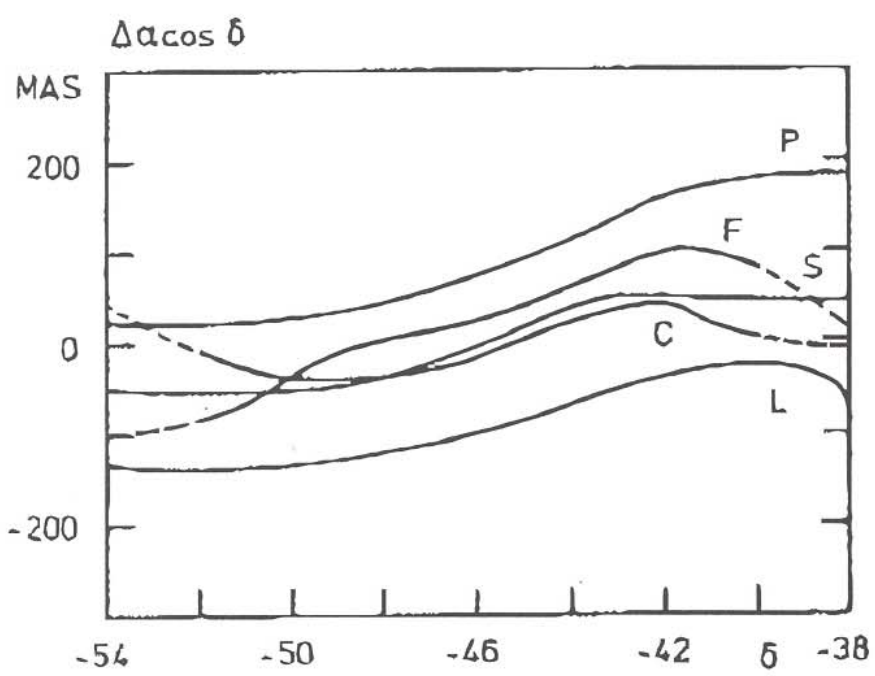


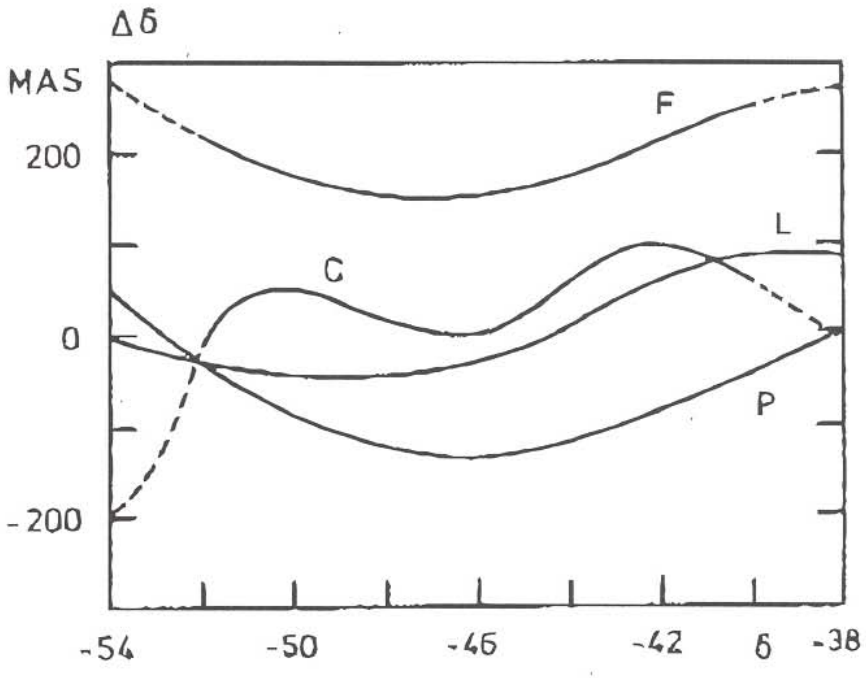
ACRS and Hipparcos



AC on HIP and Hipparcos

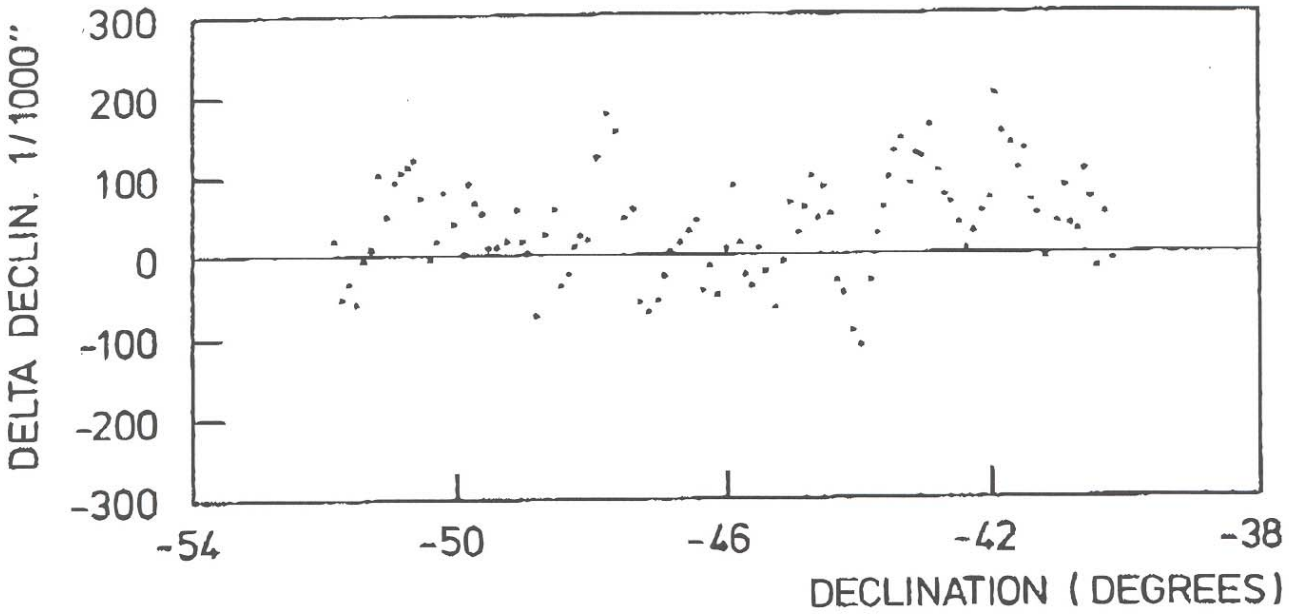




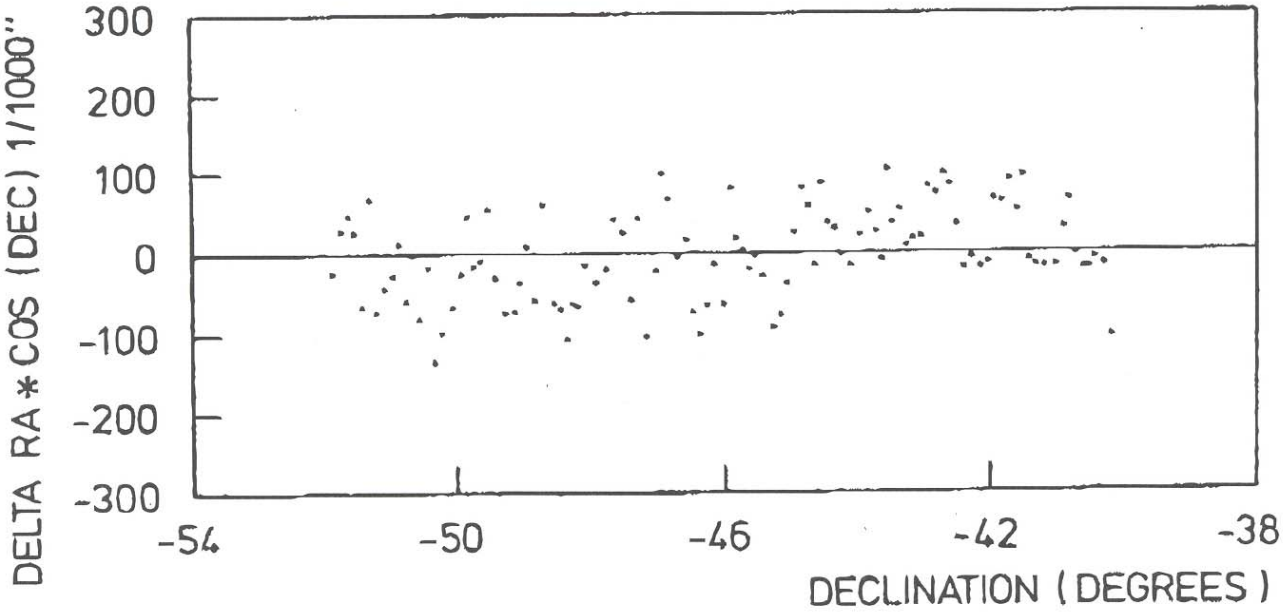


L = Leoncito - FK4, P = Perth 70 – FK4, S = Santiago – FK4

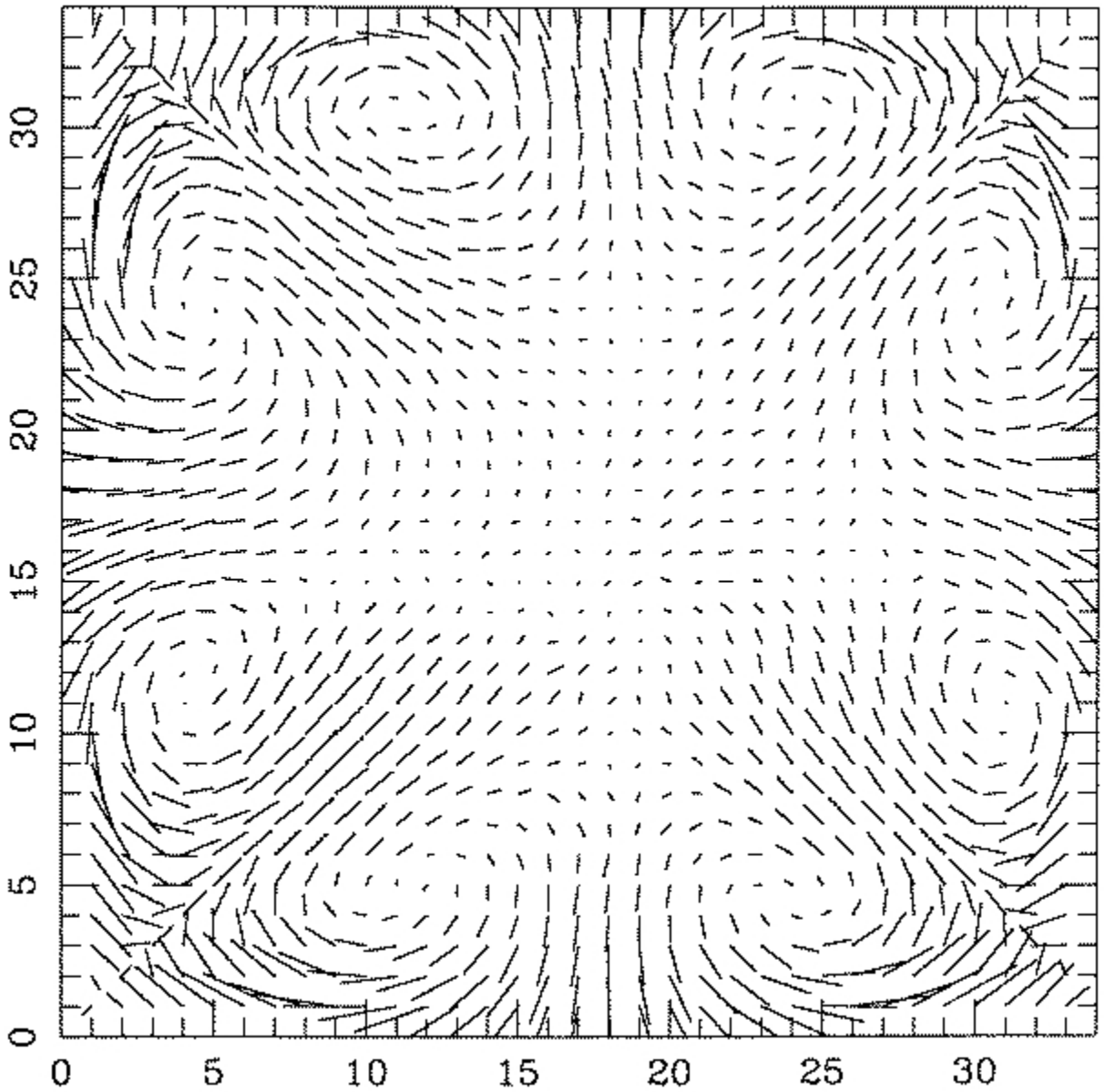
C = CPC2 (BA) – SRS, F = CPC2 (BA) – FK4



BA position – SRS Catalog



Taff-o-gram POSS Plate



Taff-o-gram for USNO-B1