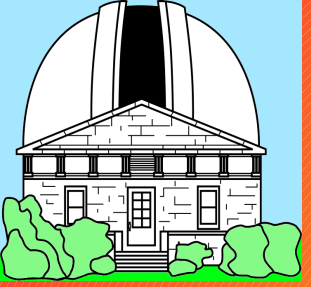
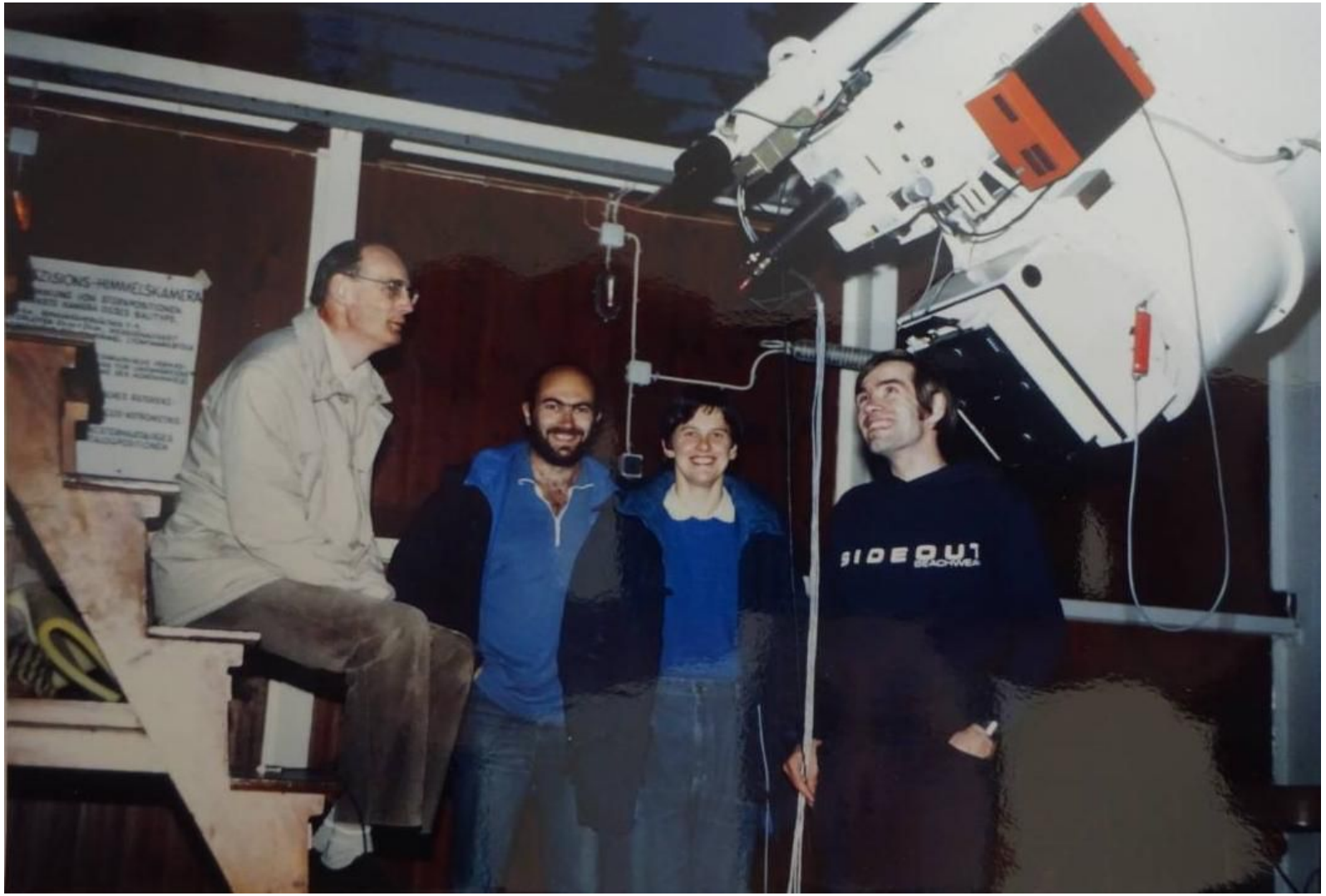


Astrometric surveys: from photographic plates to CCDs

Norbert Zacharias

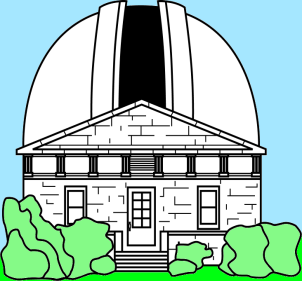
U.S. Naval Observatory
Astrometry Department
Optical Reference Frame Div.

norbert.zacharias@navy.mil
nzIAUc8@gmail.com



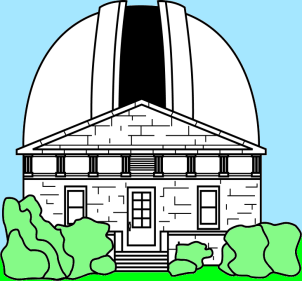
This talk is dedicated to

Christian de Vegt (1936-2002) and Lars Winter (1960-2018)



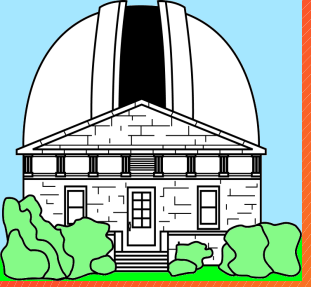
Disclaimer ...

- here only deal with:
  - ground-based (so no Hipparcos, HST, Gaia)
  - involving small telescopes (up to about 1-meter aperture)
  - involving astrometry as a main driver
- do not deal with:
  - transit circle astrometry
  - scanning instruments (SDSS, CCD transit instruments)
  - specific trigonometric parallax programs (classical refractors)



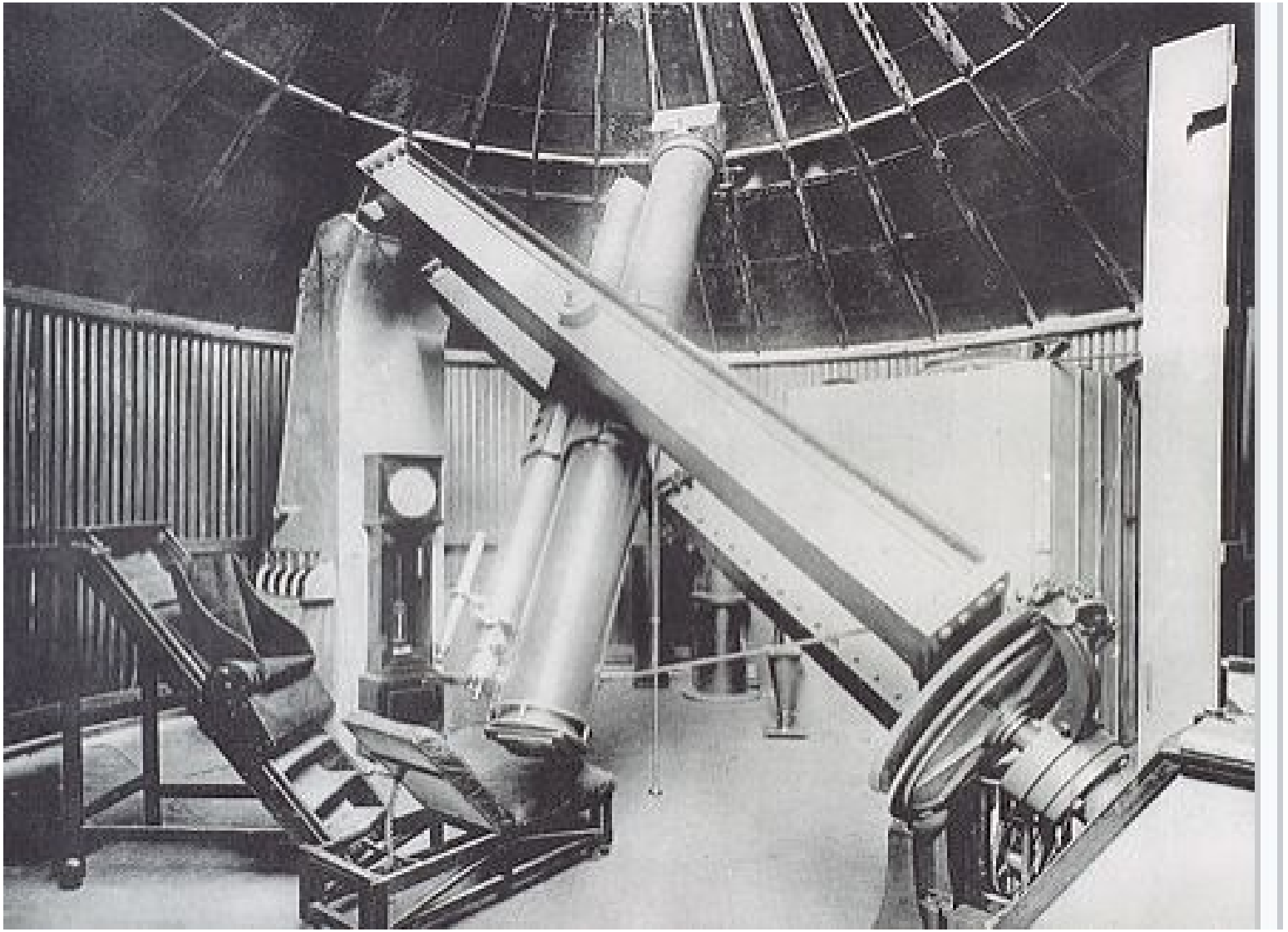
Layout of this talk

- Early astrometric surveys
  - Astrographic Catalog, AGK2, AGK3
- More astrometry on photogr. plates
  - Schmidt surveys, astrographs
- Plate measuring machines
  - PDS, StarScan, NOFS, DAMIAN...
- Astrometric surveys with CCDs
  - UCAC, PTF, ZTF, URAT
- What is next ? (for USNO)

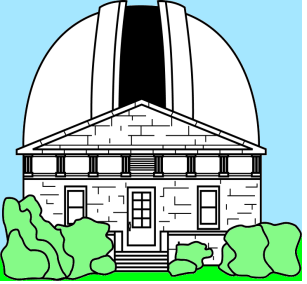


Early astrometric surveys

Astrographic Catalog

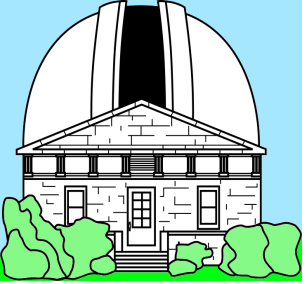


Normal Astrograph, Sydney Observatory



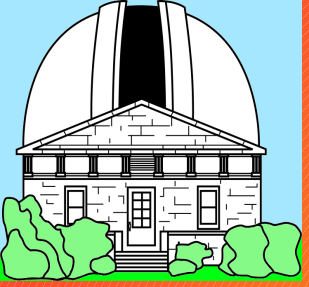
AC project

- begin in 1880s, continue for decades
- over 20 observatories involved
- use same type of telescope (60 “/mm, 2-lens, 2x2 deg)
- limiting magnitude about B = 13 … 14
- more stars observed than can be measured at the time
- first time to accurately map the sky (positions)
- basis to obtain proper motions

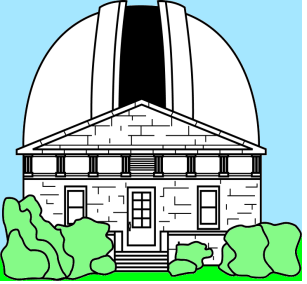


AGK2, AGK3

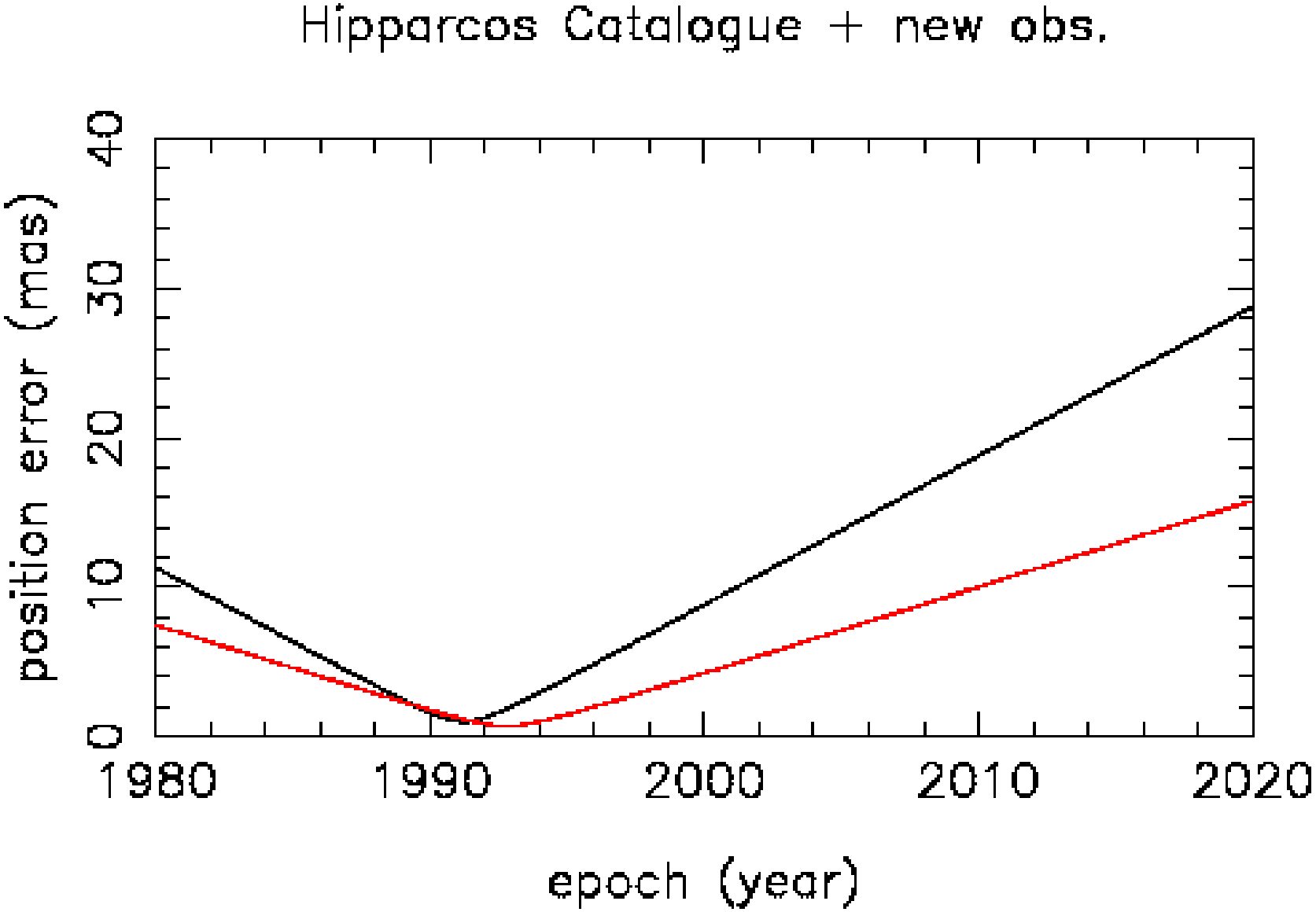
- Hamburg Observatory (+Bonn, Pulkovo)
- about 1930 and 1960 epochs, 5 x 5 deg
- decades long measure and reduction process:
  - 1-axis screw plate measure machines
  - pick “only” 186,000 stars to about B = 11 mag
  - foundation for proper motions, dynamic of Milky Way
- AGK2 plates slightly better quality than AGK3
  - finer grain, final measurement with StarScan around 2000
  - nearly 1 million stars: reductions run in 0.5 hours

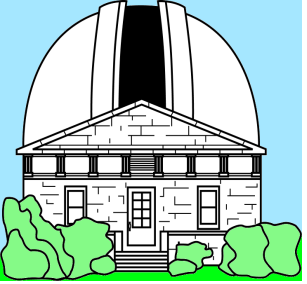


More astrometry on photographic plates



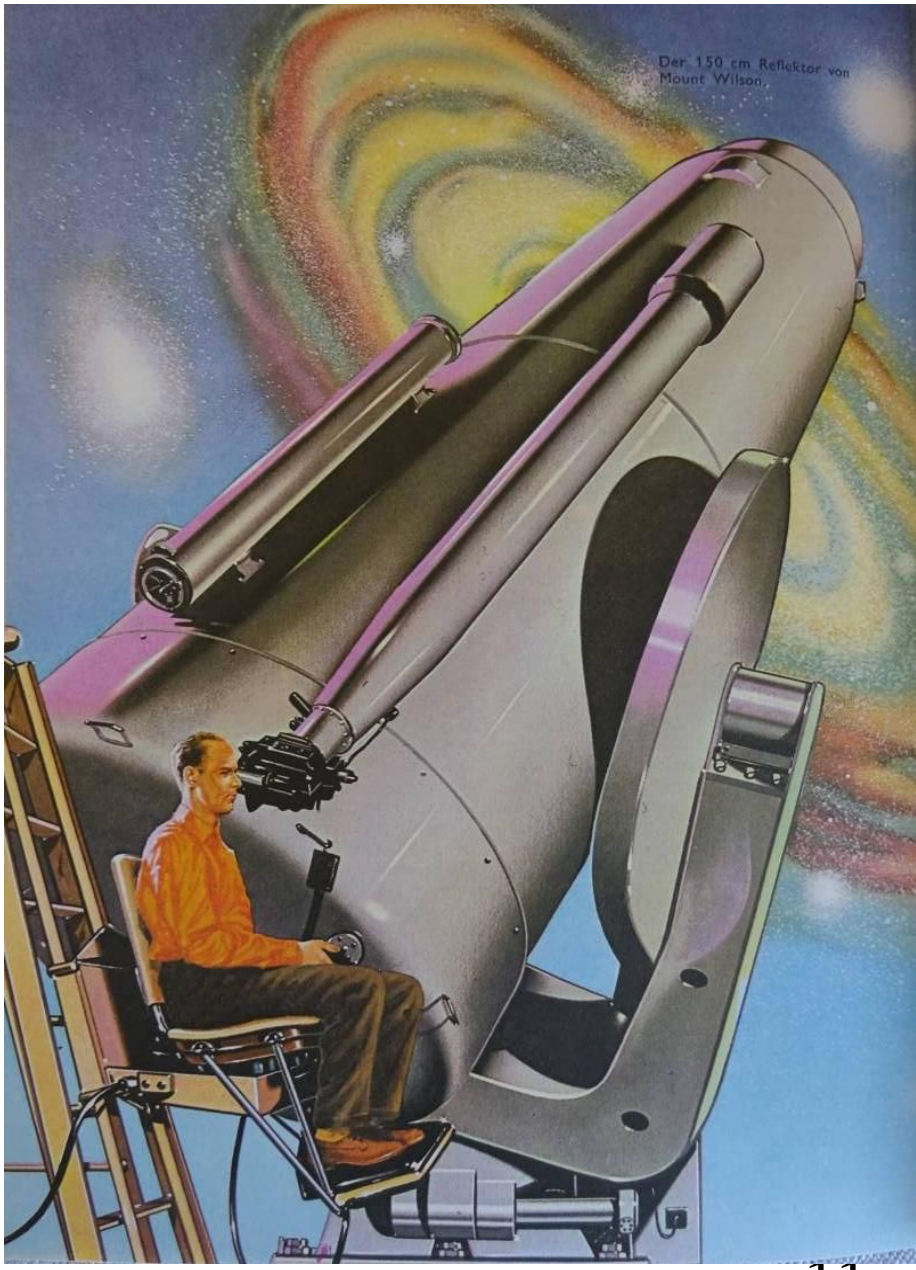
position error increases with time

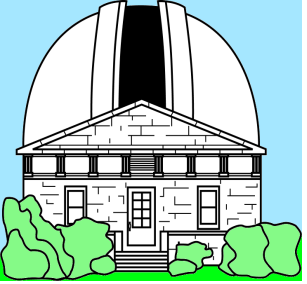




Schmidt plate surveys

- Palomar Observatory lead
- 2 epochs
- later extended to south
- over 6 x 6 deg FOV
- multiple colors
- single overlap (per color)
- go very deep: 20th mag
- initially = “atlas”, no technology to measure plates





NPM, SPM

- Lead by Yale University
- Northern proper motion survey (Lick)
- Southern PM survey (El Leoncito)
- 50cm double astrograph (blue, yellow)
- 4-meter focal length (50 “/mm)
- to about 17th mag, incl. galaxies
- 2 epoch observations (> 20 yr apart)
- use of objective grating (reach B=6mag stars)
- more accurate than Schmidt plates

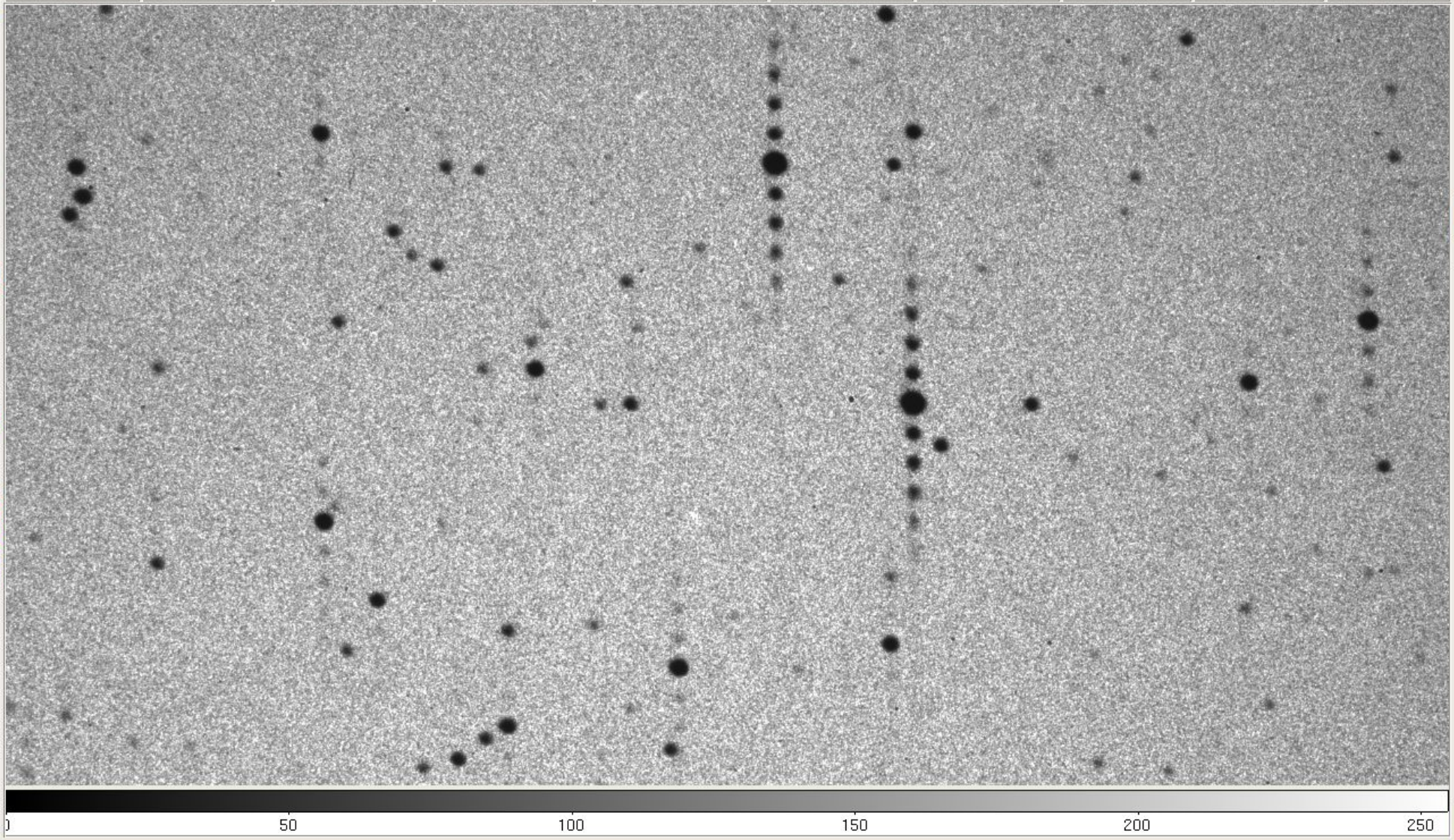
SAOImage ds9

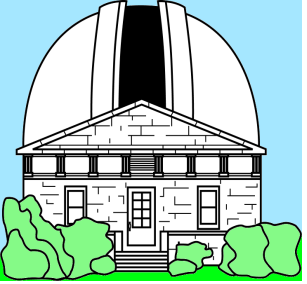
File Edit View Frame Bin Zoom Scale Color Region WCS Analysis Help

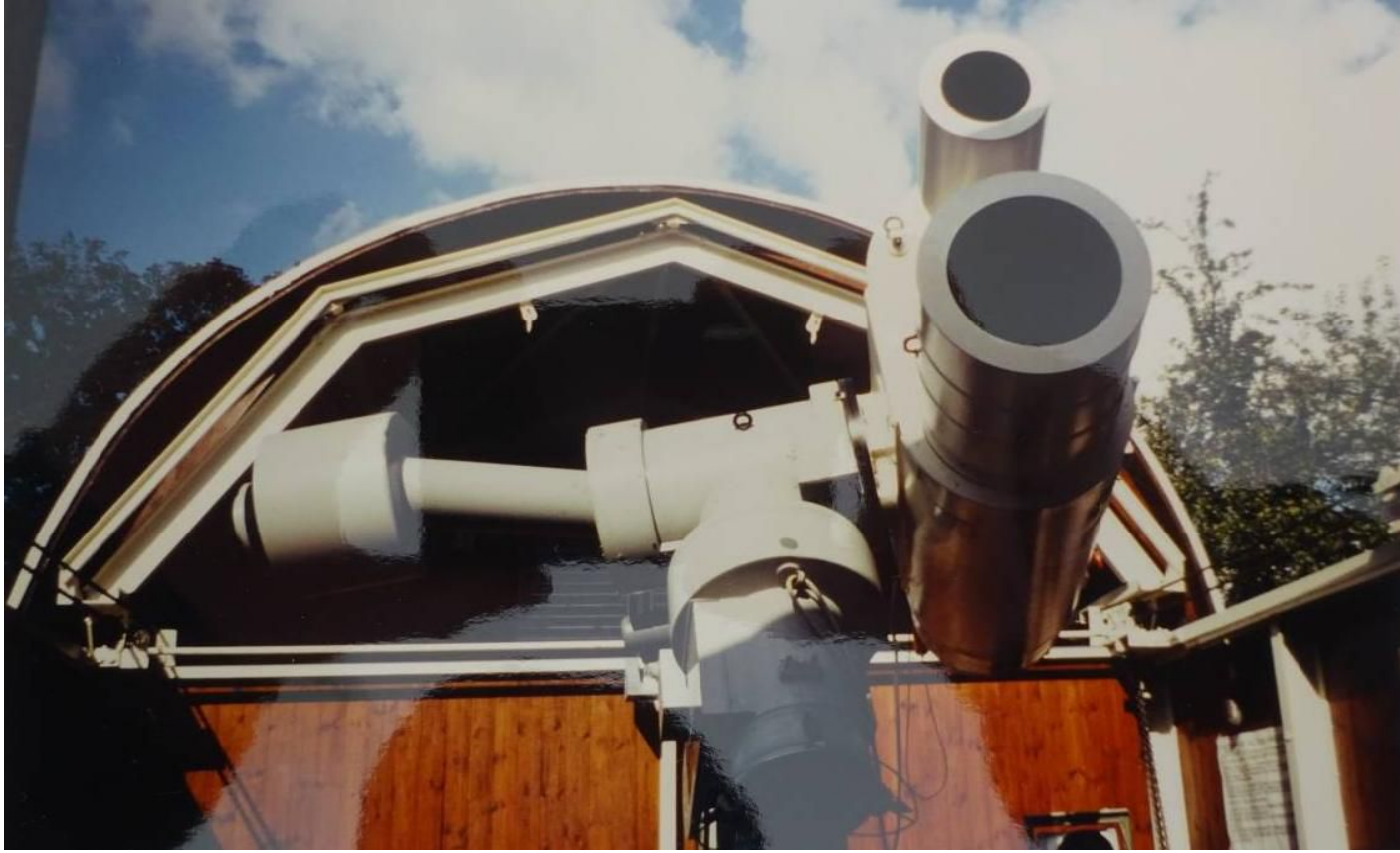
File	yy0104.444			
Object	YY0104			
Value				
WCS				
Physical	X		Y	
Image	X		Y	
Frame1	Zoom	1.000	Ang	0.000

File Edit View Frame Bin Zoom Scale Color Region WCS Help

about open save img save fits save mpeg header source print page exit







- late 1970s
- Zeiss, 5-lens
- F = 2m, f/10
- 100 “/mm
- 6 x 6 deg FOV
- Kodak microflat plates
- radio-optical reference frame
- operate until mid 1990s, basically run out of plates !

Hamburg Zone astrograph

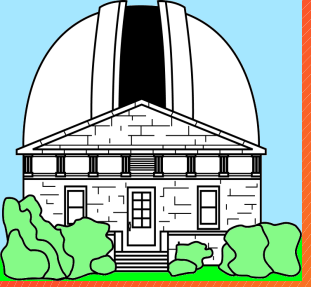
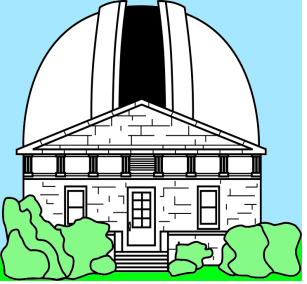


Plate measuring machines



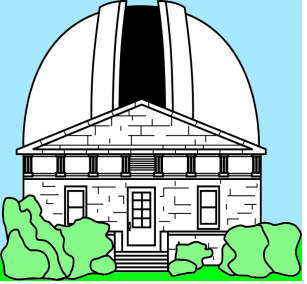
Hamburg machine

- 1970s Mann-comparator
- manual (punched cards)
- later automated
- sub-micrometer precision
- up to 24 cm sq. plates
- 1st astrometric reduction of a plate with prelim. Hipparcos data

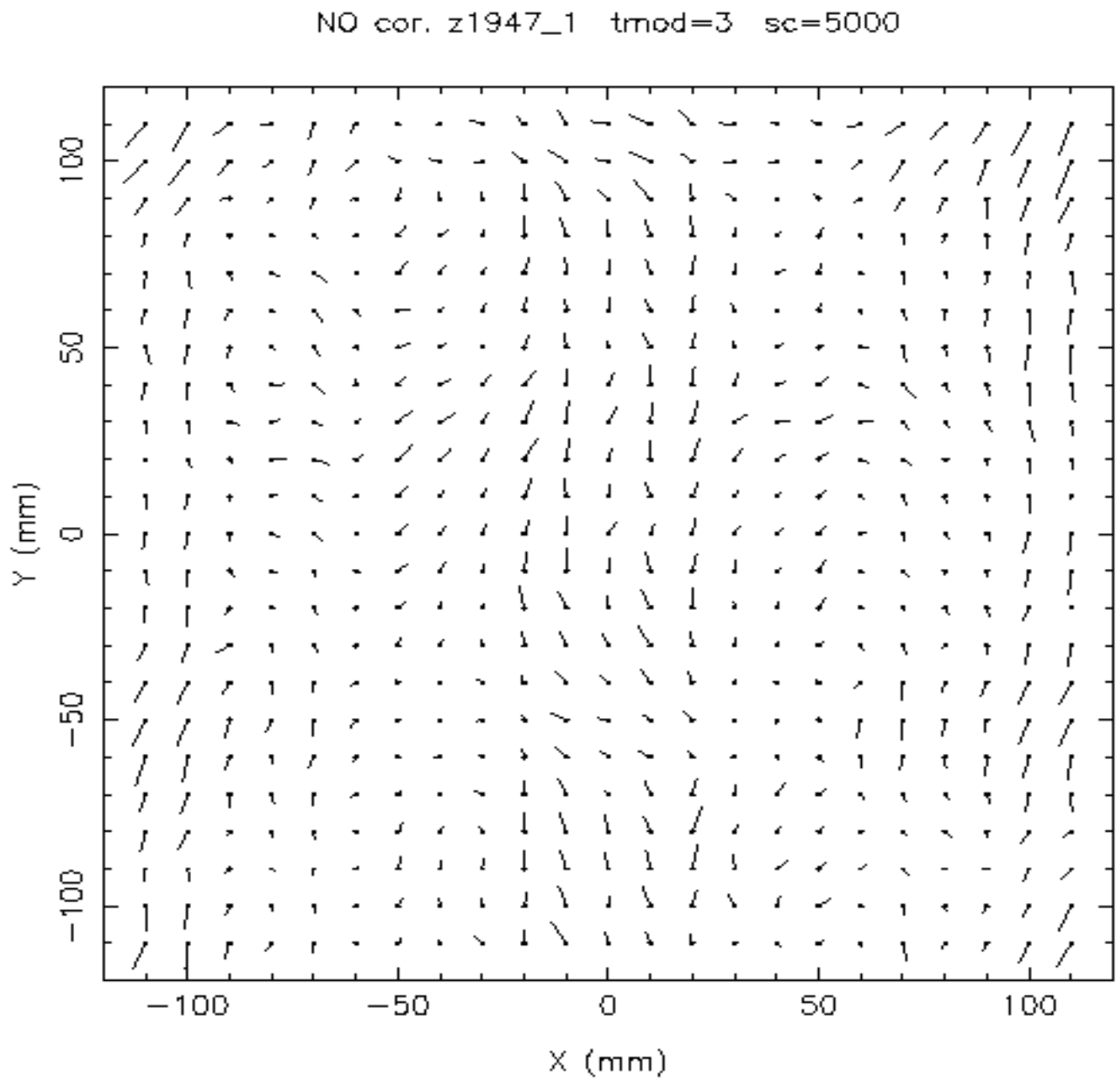
Scan of Schmidt survey plates PDS, Super Cosmos, PMM

- PDS
  - Perkin-Elmer densitometer
  - “pretty darn slow” (7 hours / plate)
  - STScI and others
- Super Cosmos
  - England, Scotland
  - one-of-a-kind
- PMM (Naval Obs.Flagstaff)
  - 4 Schmidt plates at a time
  - CCD cameras

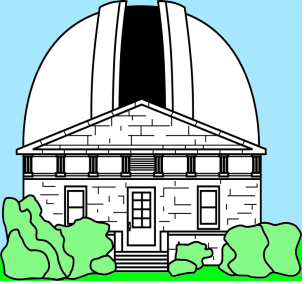

StarScan plate measure machine
Washington, DC



StarScan calibration



2 um
x,y table
errors

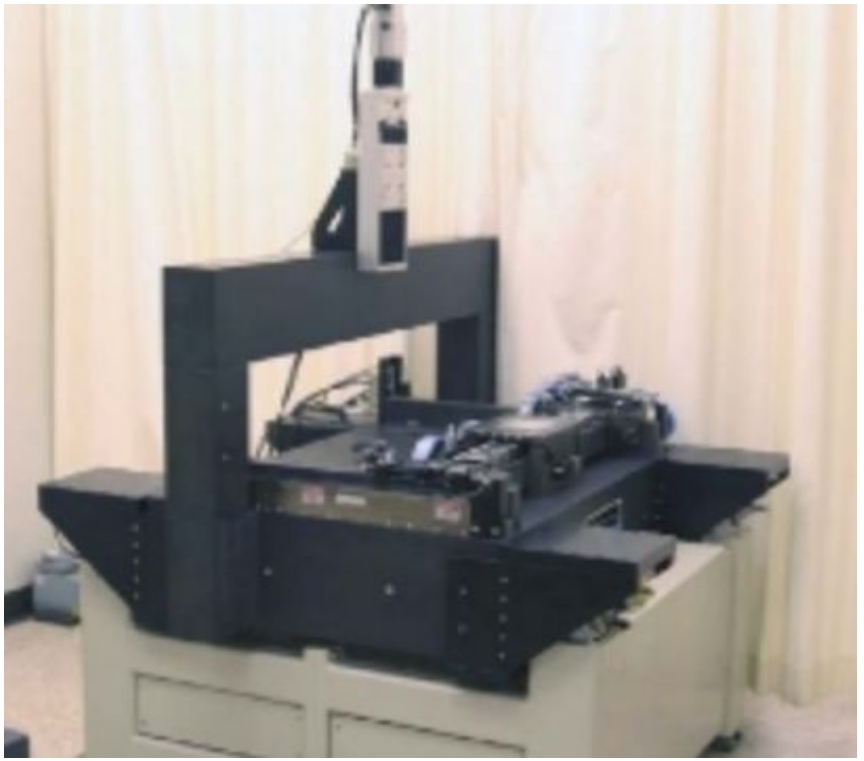


StarScan plate measuring

- early epoch data for proper motions for UCAC
- CCD camera, step-stare mode
- accurate to <= 0.5 micrometer absolute
- 1930 AGK2: 1,900 plates
- 1976..1995 ZA: 2,300 plates
- 1983..1990 BB: 900 plates

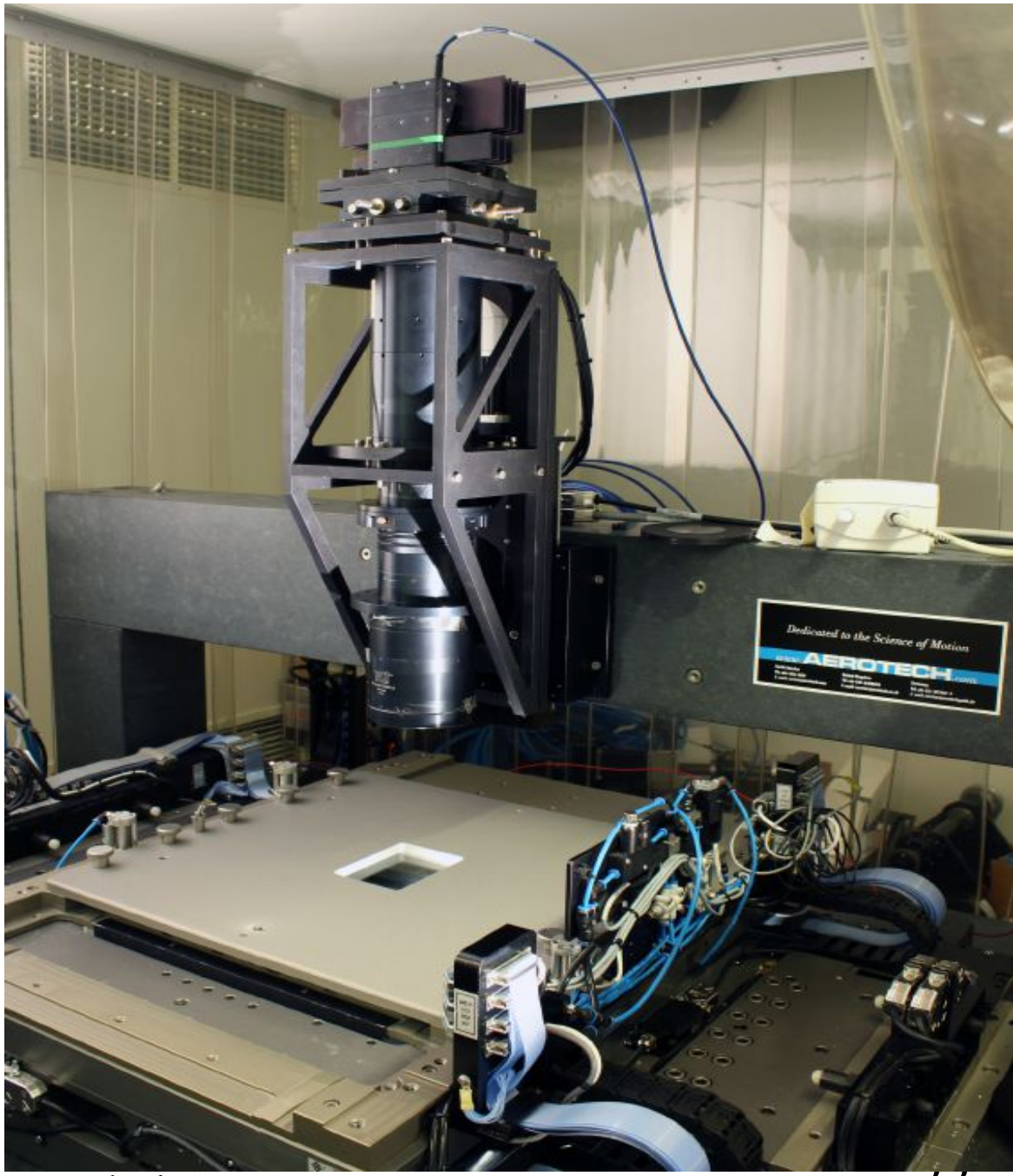
Digital Access to a sky century @ Harvard (DASCH)

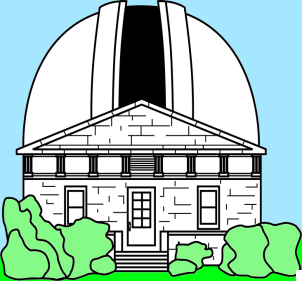
- begin operations in 2005
- 8x12 inch plate in a minute
- Aerotech table
- Sill telecentric lens
- 4k x 4k CCD, 11um, 12bit
- 323,000+ plates by 2019
- mainly photometry:
  - 0.1 mag light curves



DAMIAN, Royal Brussels Observatory

- ultimate in accuracy
- 10 nm stability
- <= 0.1 microm. perform.
- 10k x 7k CMOS
- 31 x 22 mm
- telecentric lens
- 3000 astrometric plates
- incl. USNO nat.satellites
- 20,000 other plates / film





Gaia takes over ...

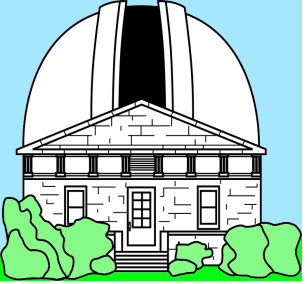
magnitude	par.err.	PM error (microarcsec/yr)	
G <= 12	5 .. 16	3 .. 8	end of 5yr mission
G = 15	24	12	
G = 20	130	65	red star
G = 20	600	300	blue star

Gaia position error (mas) as function of epoch

PM error	1990	1960	1930	1900
10 uas/yr	0.3	0.6	0.9	1.2
25 uas/yr	0.7	1.4	2.2	2.9
100 uas/yr	2.6	5.6	8.6	11.6
600 uas/yr	15.6	34.	52.	70.

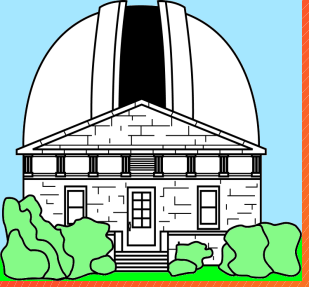
estimated best precision of photogr.data:

1990	0.3 um =	15 mas	Lick astrograph
1990	0.3 um =	30 mas	Hamburg Zone astrogr.
1960	0.5 um =	30 mas	Schmidt plates
1930	0.3 um =	30 mas	AGK2 plates
1900	0.5 um =	30 mas	AC plates

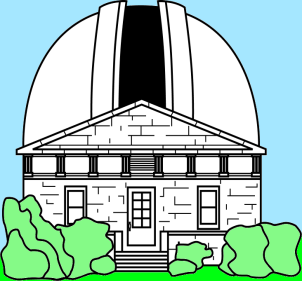


need a science case ...

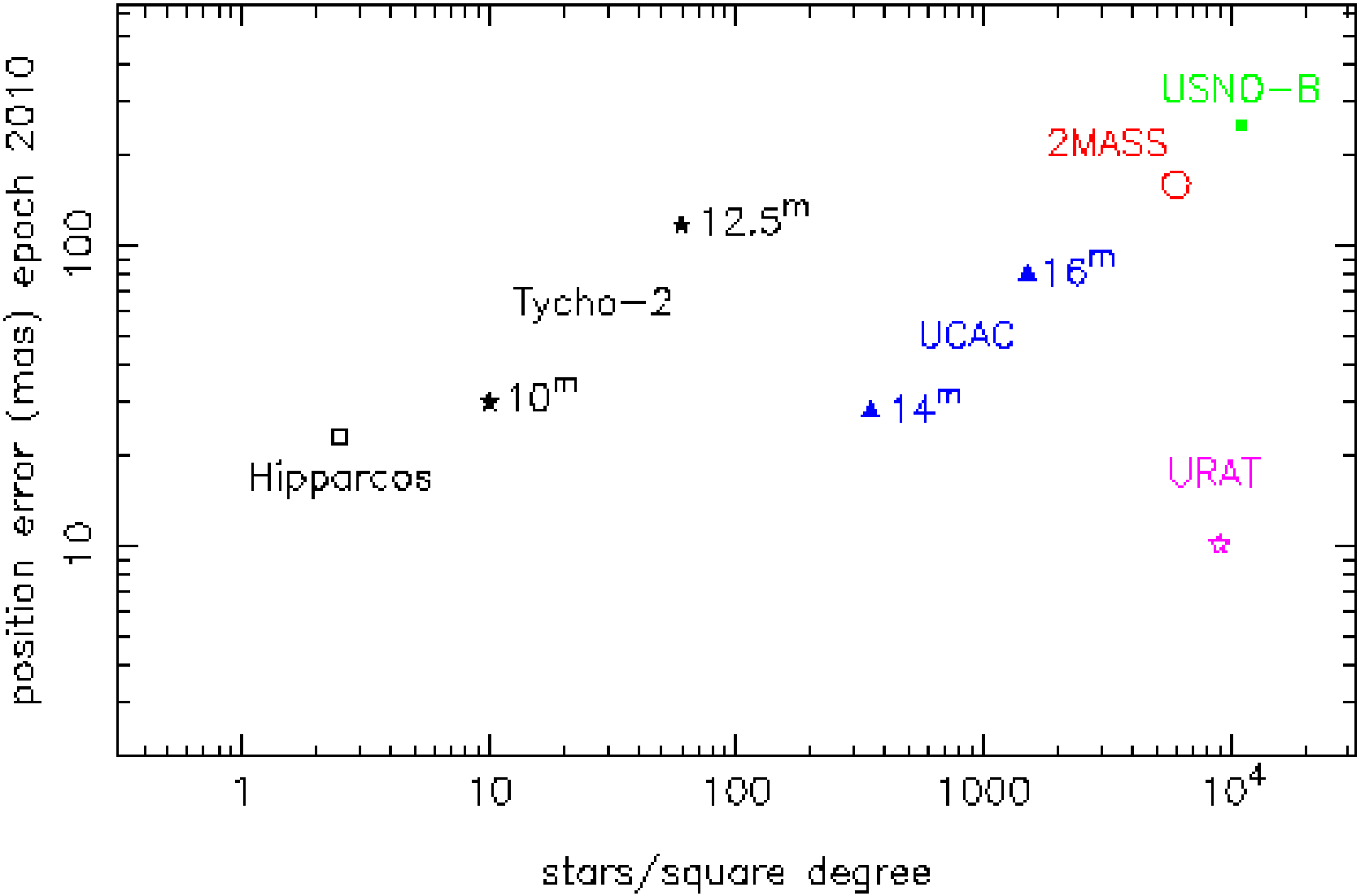
- most photographic plates: no more gain for astrometry
  - Gaia positions propagate back to early epoch = better than plates
    - linear proper motions : done
  - exceptions: whenever specific epoch data are needed:
    - complex moving objects in general (orbits ...)
    - satellites of Mars, Jupiter, Saturn...
- case is different for photometry, transient phenomena
  - historical record of events



Astrometric surveys with CCDs



accuracy of catalogs

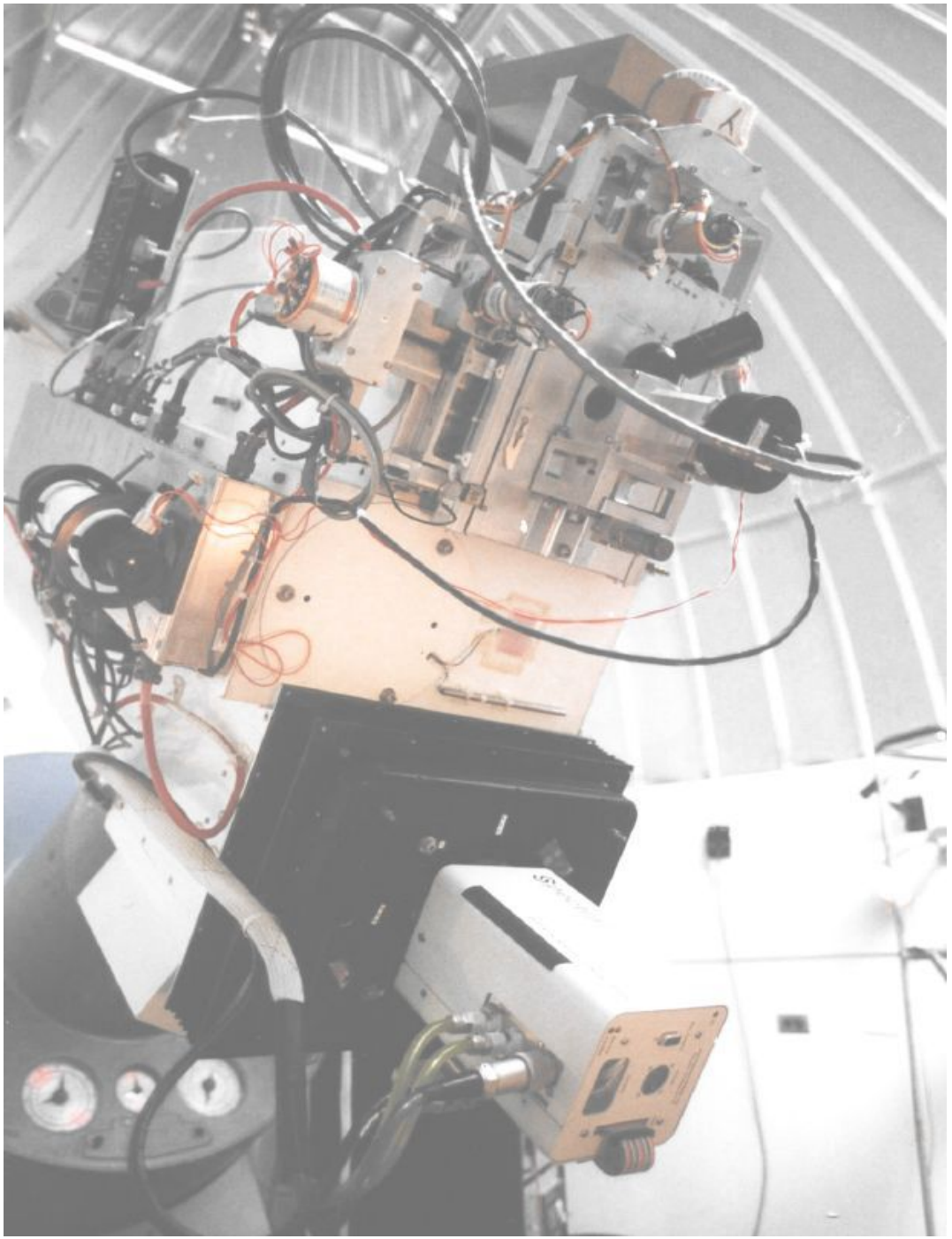


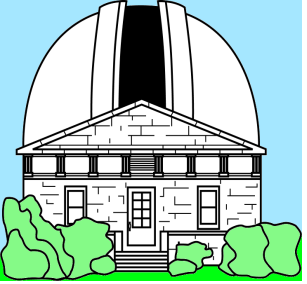

observing at CTIO

x-y slide

backend of USNO astrograph 1997

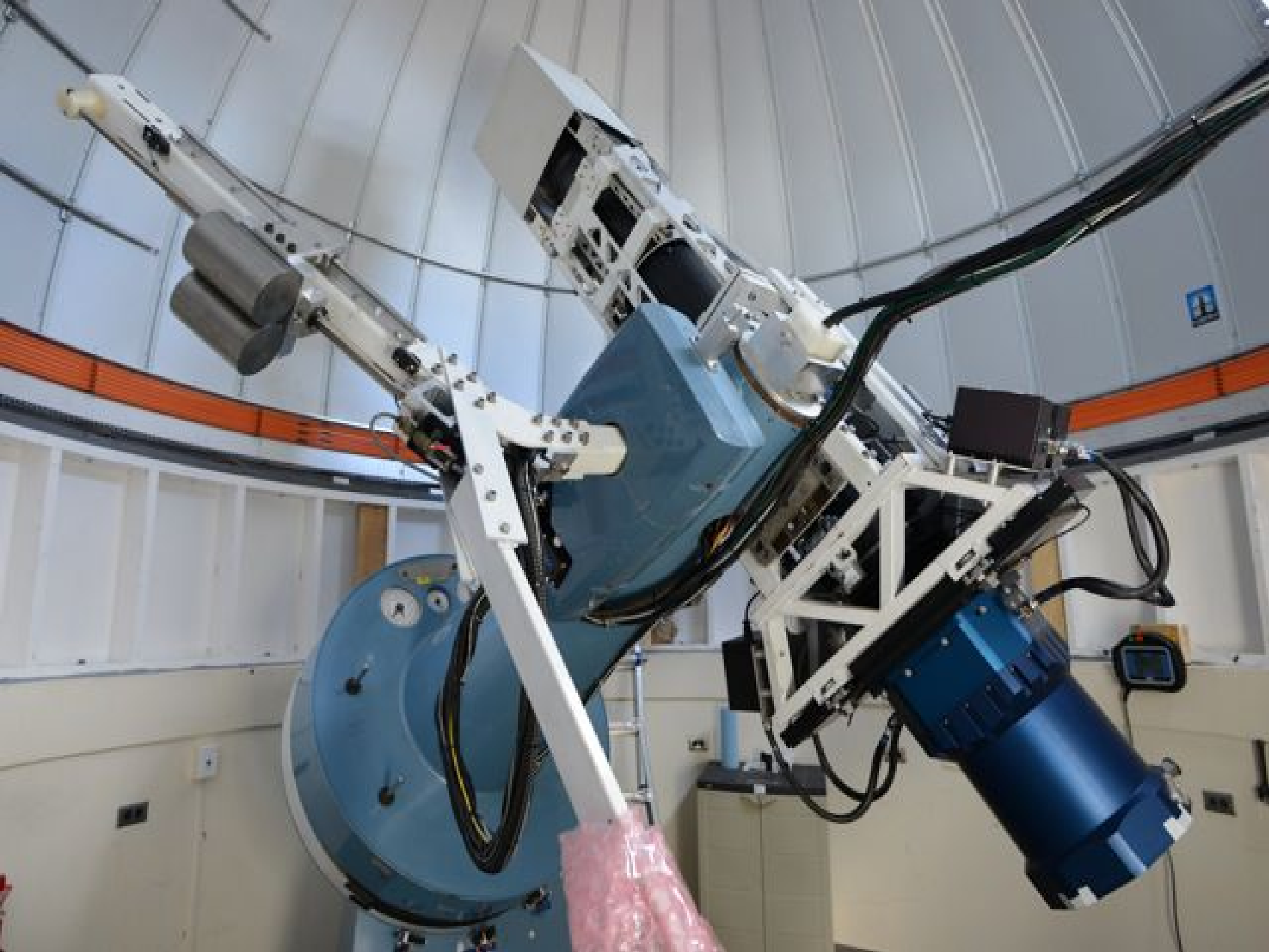
4k camera

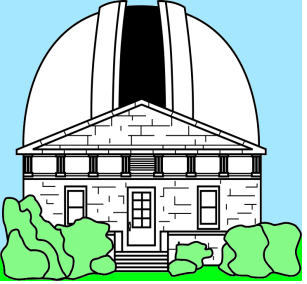




UCAC details

- first astrometric survey with CCD (1 sq.deg FOV)
- 1997 – 2004 (all-sky completed, CTIO, NOFS)
- 579 – 642 nm single bandpass
- R = 8 to 16 mag
- positions accurate to 20 mas (10 – 14 mag)
- incl. proper motions (with various early epoch catalogs)
- final release: UCAC4 (2012) incl. photometry
- UCAC2 / UCAC4 : 560 / 750 citations by today
- UCAC5 = UCAC4 + Gaia DR1 for new proper motions

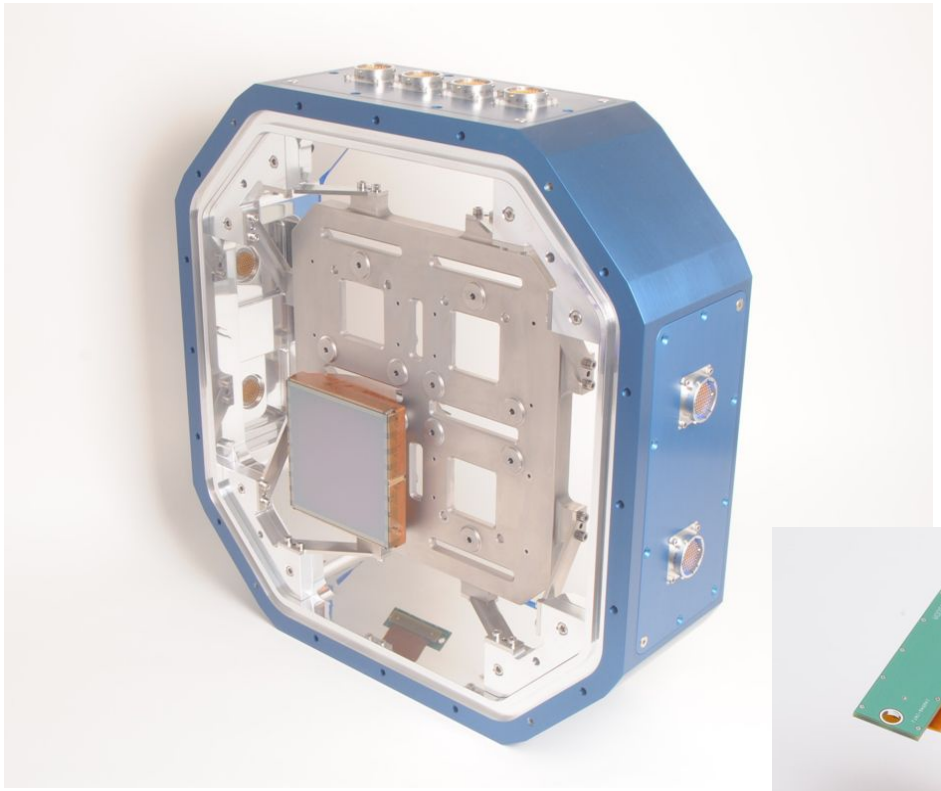


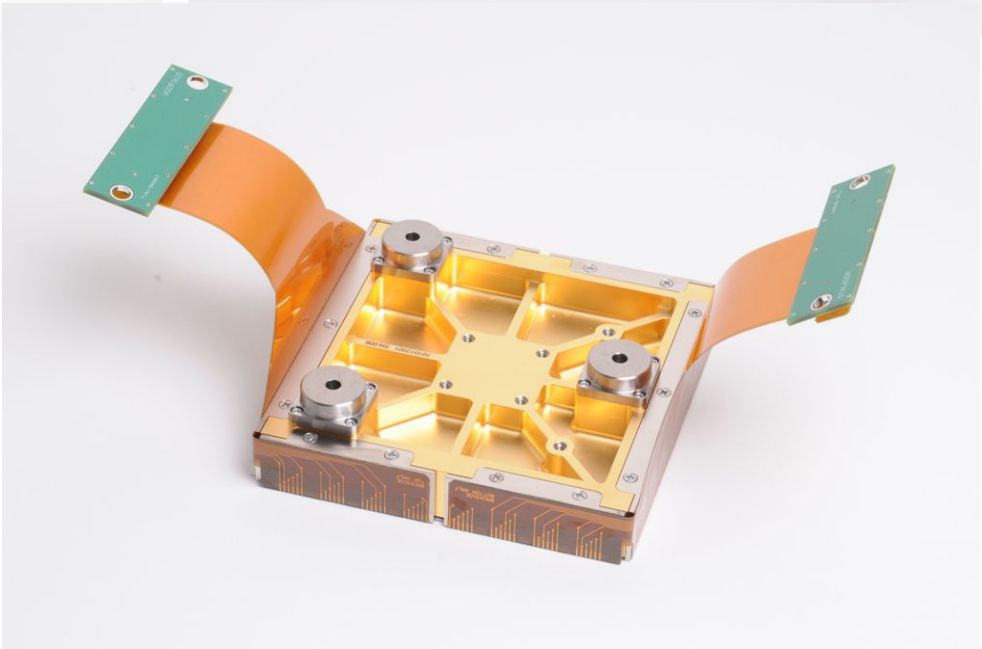


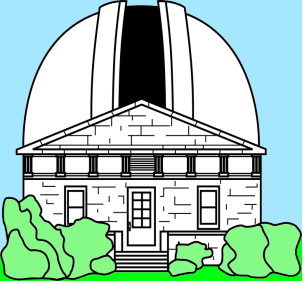
URAT project

- use "red lens" (UCAC) with modified astrograph
- STA detector: (10,560 by 10,560 pixels, 9 um)
  - 10k test camera: 1st light October 2007
  - "4-shooter" camera ordered in 2008
- URAT observing program
  - 1st light of URAT in Washington, DC: September 2011
  - URAT survey at NOFS (2012-2015)
  - CTIO: Oct 2015 – June 2018: bright star survey south
  - over 300,000 exposures taken, each 28 sq.deg
- URAT is now available for collaboration or external deployment – any good ideas ? Please contact me.

spring 2010, 10k packaging

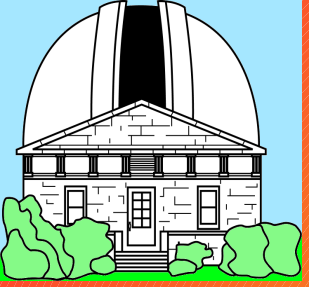




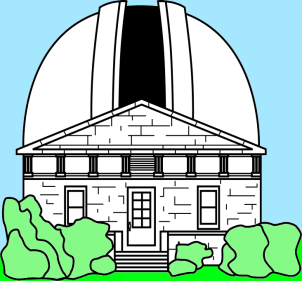


2 surveys at CTIO

- General sky survey (-90 to +25 deg Dec):
  - 4.5 mag attenuation grating, 60, 30, 2x 10 sec expos. / field
  - covers URAT (about R) mag 3.7 to 16.5
  - about 50 expos. / year per target
- Brightest stars (-90 to +25 deg Dec):
  - 4.5 mag grating + neutral density spot (another 4.5 mag)
  - individual target all stars from Sirius to about R = 4.5 mag
  - multiple exposures per pointing, 60, 30, 10, or 5 sec
  - about 20 epochs per year, times numb. expos. each pointing
- for more see proceed. IAU S.348

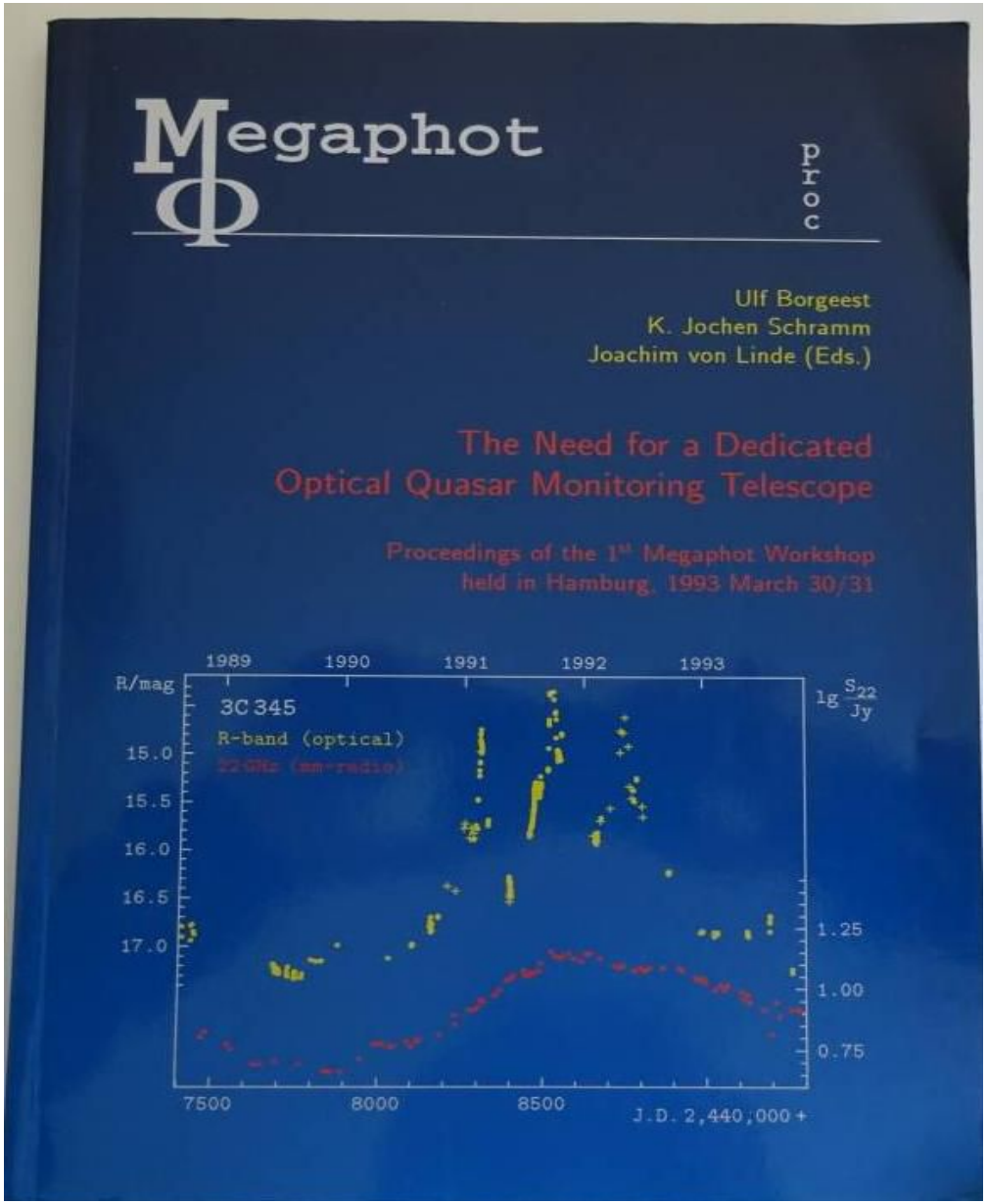


What is next ?
(for USNO)



Quasar monitoring ...

- Gaia era
- investigate radio-optical position offsets
- high cadence observations
- correlate with photometry …
- … not so new … Hamburg Obs. proposal 1993 ...



PlaneWave CDK1000

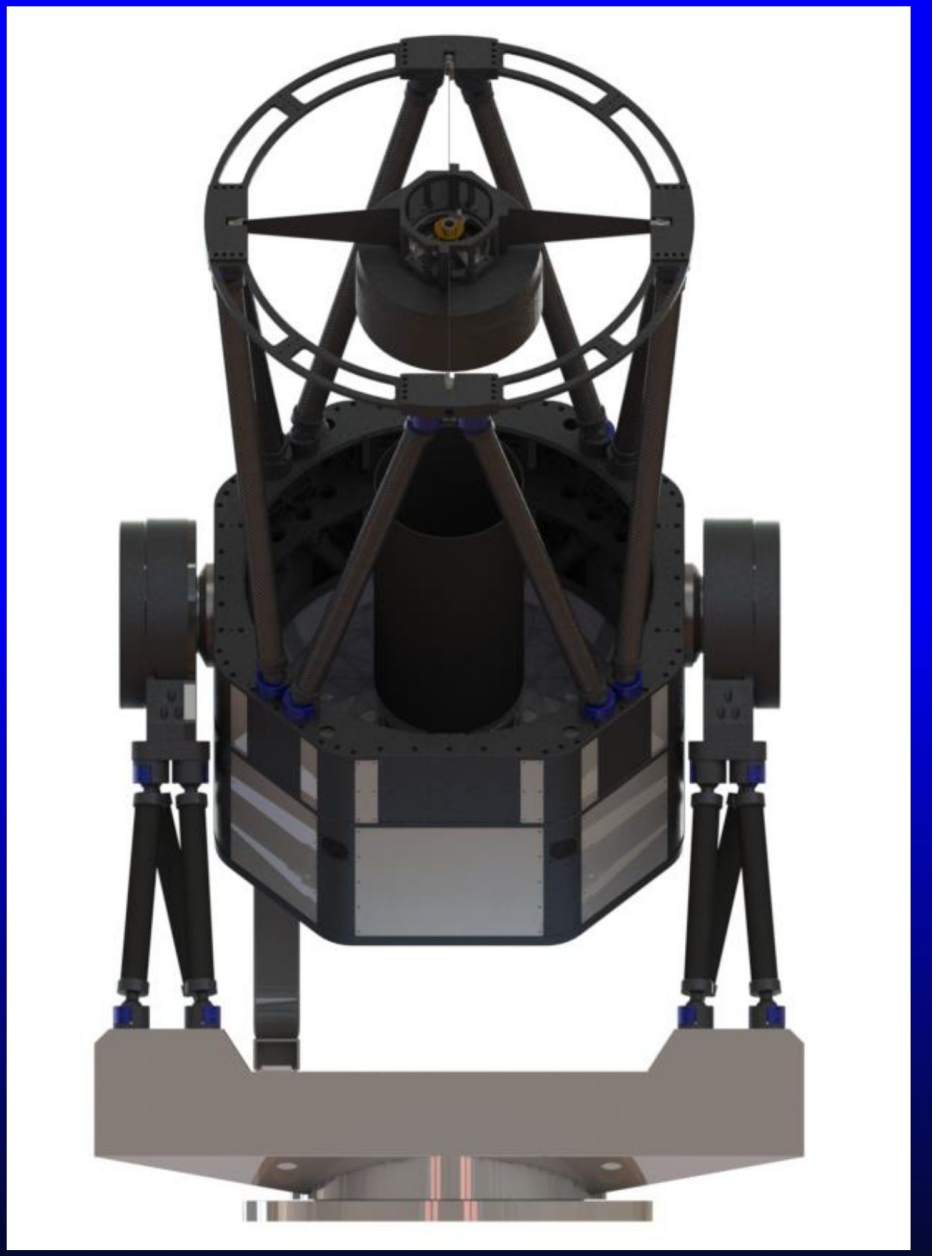
Fits in 16’ dome

Focal plane is at eye height

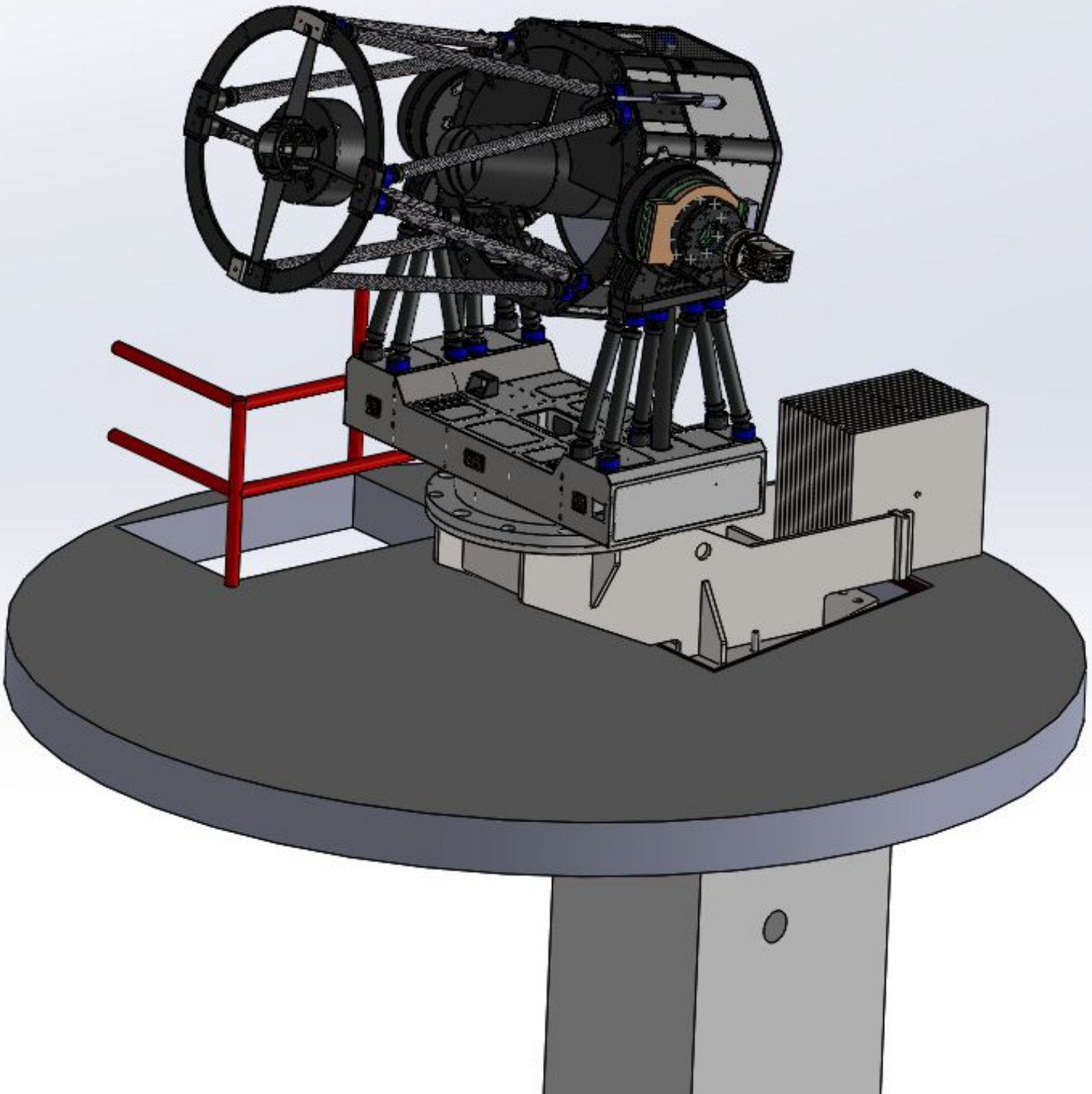
Optical benches on the sides are de-rotated

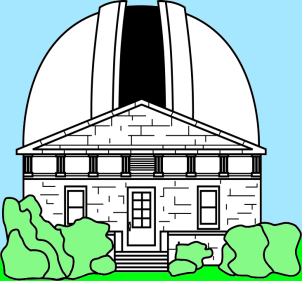
All cables and electronics are inside truss poles, forks, base and cable tray

Easy access to cables and electronics

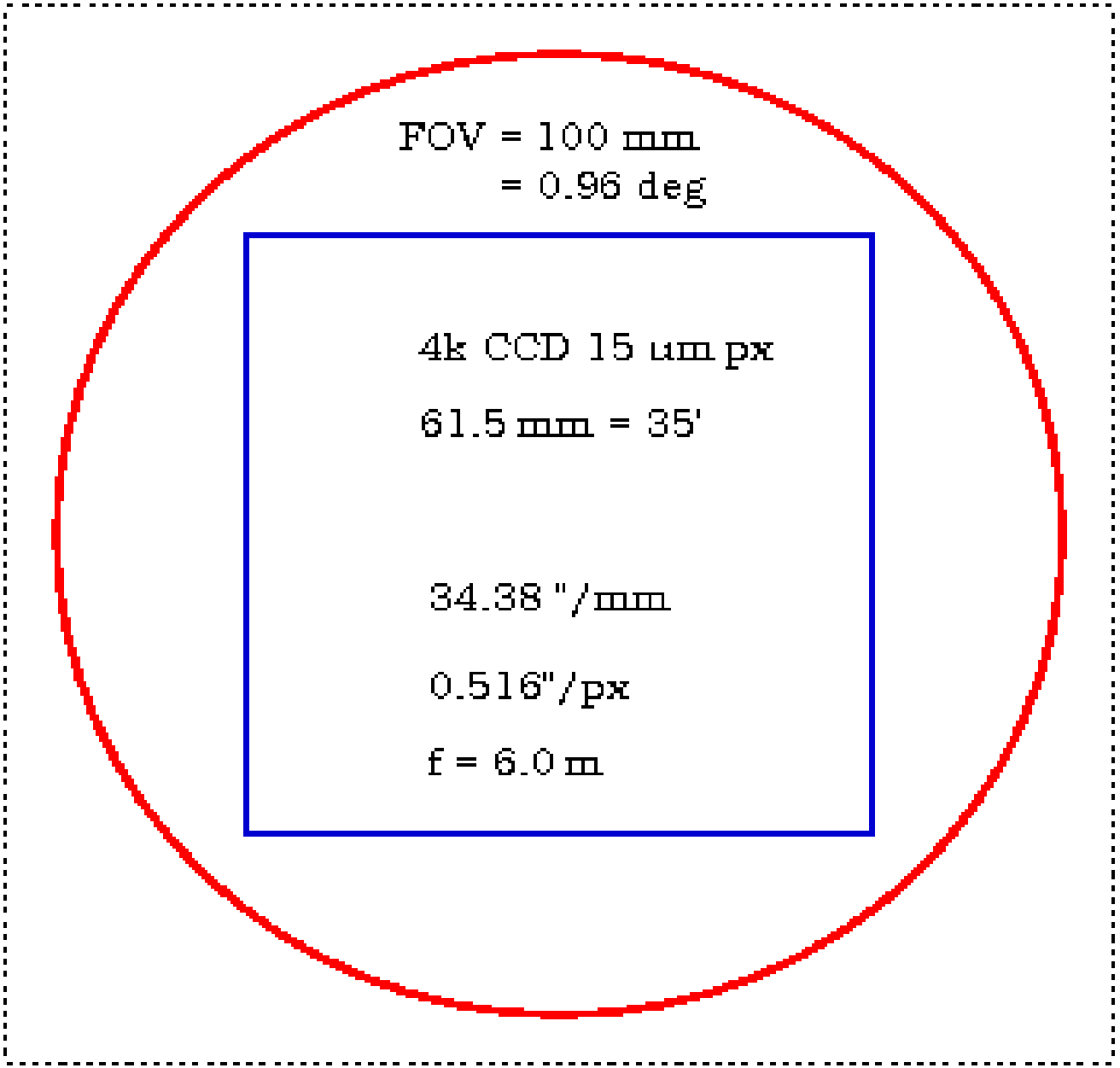


- 1.0 m apert.
- f = 6.0 m
- 2 foci
  - optical
  - near-IR
- robotic



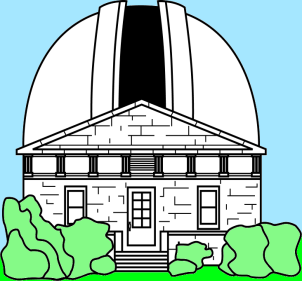


focal plane with single CCD



Princeton Instruments camera

- 4k by 4k E2V CCD
- 4 port low-noise read
- lifetime vacuum
- therm.electic cooling to -90 C
- No more liquid N2



Conclusions

- Astrometry is the foundation for astrophysics
  - 1st large astrometric surveys: aim at mapping the sky (once)
  - next step: get proper motions = decades long projects, 2 epochs
  - parallaxes on massive scale only in recent history
- Results improve over time with technology improvement
  - manual plate measuring machines, 1-d, 2-d, then automation
  - technology only recently advanced enough to allow complete extraction of data from photographic plates
- leap in accuracy with CCD all-sky surveys
- Gaia data now better than plates or CCDs at any epoch
  - need astrometry from historic plates only for complex motion
- Photometry: different story, historical record is unique