The Future of Astrometric All-Sky Surveys

Norbert Zacharias
U.S. Naval Observatory
Washington, DC

nz@usno.navy.mil

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layout of talk

(1) astrometric surveys

(2) URAT

(3) OBSS

(4) MAPS

astrometric surveys

what is an astrometric telescope?

historical examples

current status all-sky data

best astrometric precision

overview future projects

what is an astrometric telescope?

- design
  - stability; small field distortions
  - image centroid the same for all colors
  - no coma (asymmetric images = trouble)
- hardware features
  - to detect and calibrate systematic errors
  - to enable a “simple model”, small error propagations
- examples:
  - reversal of astrograph: East/West of pier
  - grating images to control magnitude equations

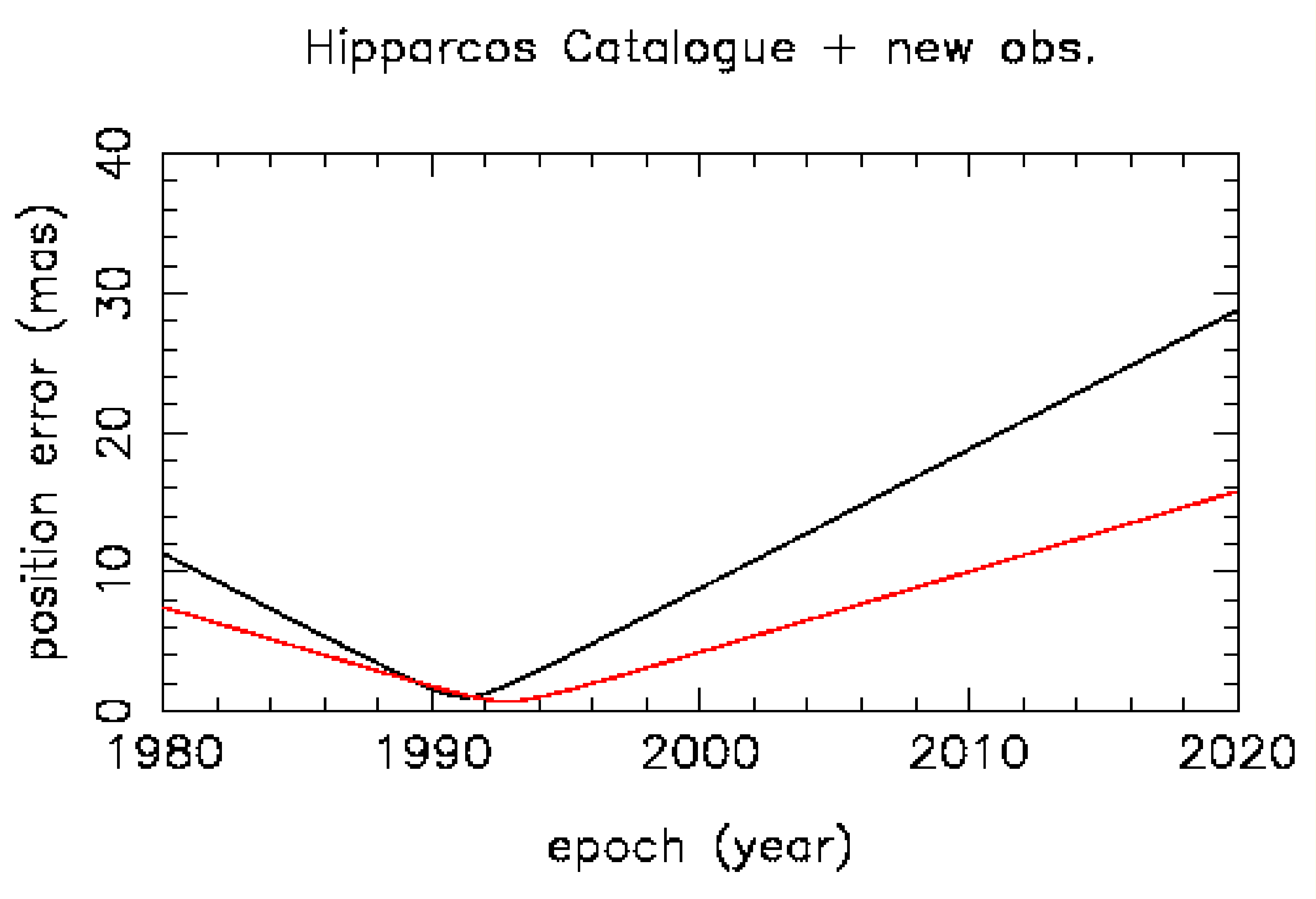
history of astrometric sky surveys

- 1890 – 1930 Astrographic Catalogue -> 13 mag
- 1930 AGK2 (north) -> 12 mag
- 1960 AGK3 (north) -> 12 mag
- 1970 CPC2 (south)   -> 11 mag
- various Zone Catalog projects (Yale ...)
- 1960 – now: proper motion surveys NPM, SPM
- 1977 – 2000 : to 14 mag, ~ 40% of sky
  - Hamburg Zone Astrograph (north)
  - USNO Black Birch Astrograph (south)
- 1998 – 2004 UCAC (first all-sky CCD survey)

currently best optical positions

- Hipparcos Catalogue
  - 100,000 stars
  - -1 to 12 mag, complete only to V = 7.3
  - mean observing epoch = 1991.25
  - mean position error (1991) = 1 mas
  - mean error proper motions = 1 mas/year
- position errors increase with time

position error = f (time)



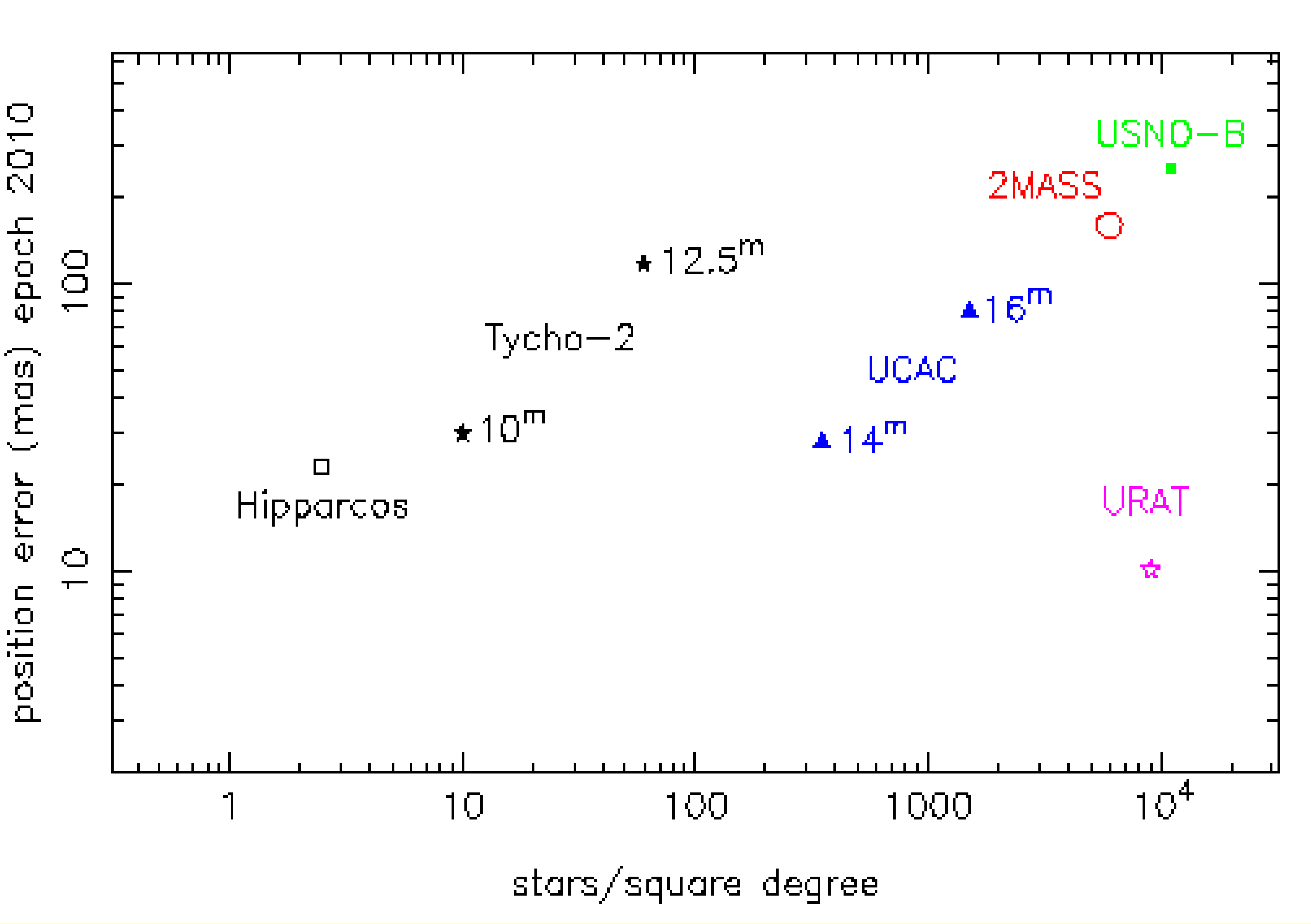
NOMAD

Naval Observatory Merged Astrometric Dataset
= currently best astrometric data = f (mag)

catalogs used	early epoch (PM)
Hipparcos	Hipparcos
UCAC2	Tycho2, “all”
Yellow-Sky	NPM, SPM data
USNO-B	Schmidt surveys

supplemented by 2MASS + USNO-B photometry
NOT a compiled catalog: pick 1 by priority

accuracy of catalogs



StarScan plate measuring machine

best astrometric precision

- assume:
  - only random errors (sqrt-n-law holds)
  - astrograph-type observing (2-dim, overlap. fields)
  - sampling is "sufficient"
  - 'well' conditioned reduction (no loss from error propag.)
  - detector with saturation limit
  - NO magnitude target (no requirement for a specific error at a specific magnitude)

- then lowest astrometric error (mission precision = mp)
  - mp ~ sml * sqrt(1/n) / d
  - sml = single meas error linear
  - n = total numb. of observat.
  - d = diameter of focal plane

- independent of:
  - wavelength
  - aperture, field of view
  - focal length, image scale
  - sampling, pixel size

future options

type	project name	cost $US	accuracy (mas)	magnitude range	remarks	launch
GB	URAT	5 M	5 – 10	(2) – 12 – 20	partly funded	2007
GB	NPOI	10 M	10 – 20	0 – 7	no south	in service
SB	SIM	900 M	0.004	0 – 20	selected stars	2011
SB	GAIA	600 M	0.015	? - 20	ESA on track	2012
SB	OBSS	750 M	0.010	? - 21+	NASA,USNO	2014
SB	MAPS	30 M	0.500	2 – 13	USNO	2008

U SNO

R obotic

A strometric

T elescope

new ground-based observational project,

partly funded

goals of the URAT project

- regular survey: 14 to 20 mag
  - ➔ overlap with UCAC stars (8 to 16 mag)
  - ➔ direct link to faint, extragalactic ref. frame sources
  - ➔ optimized for astrometry, absolute positions
- 5 mas positional accuracy
- option for bright stars (if needed)
- all sky: 2 locations (north and south)
- robotic: low operation costs
- multiple overlap in 1 - 2 years per hemisphere

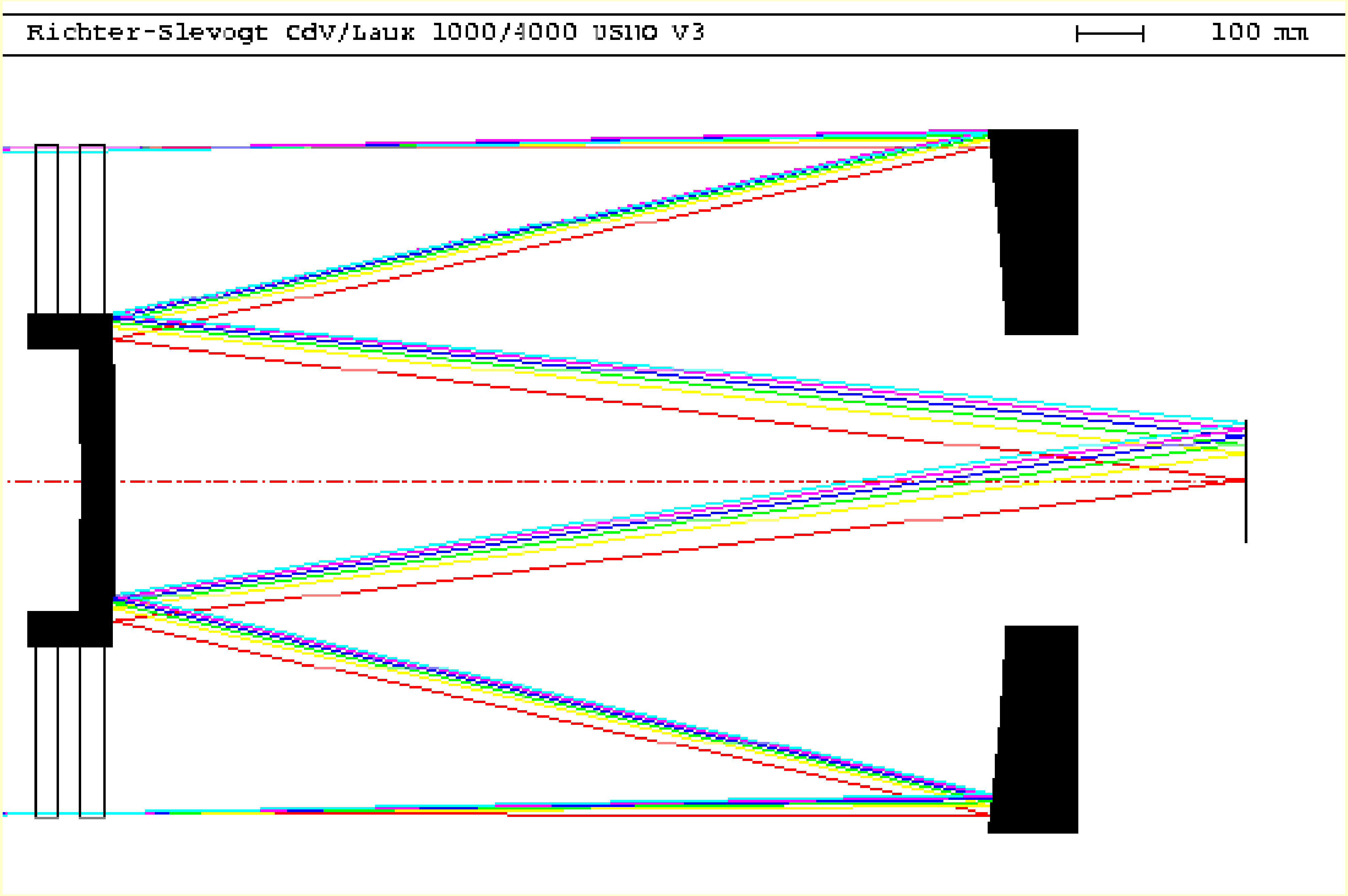
science justification

- high precision, high accuracy positions:
  - factor of 10 better than before
  - small systematic errors; solar system dynamics
  - inertial frame, strong link radio-optical frames
  - reference stars for LSST, PanSTARRS, ...
- absolute parallaxes (distances) millions stars
- absolute proper motions:
  - improve proper motions by factor of 2
  - galactic kinematics studies
- all sky accurate photometry (1 band)
  - supplement 2MASS and Schmidt surveys

project realization

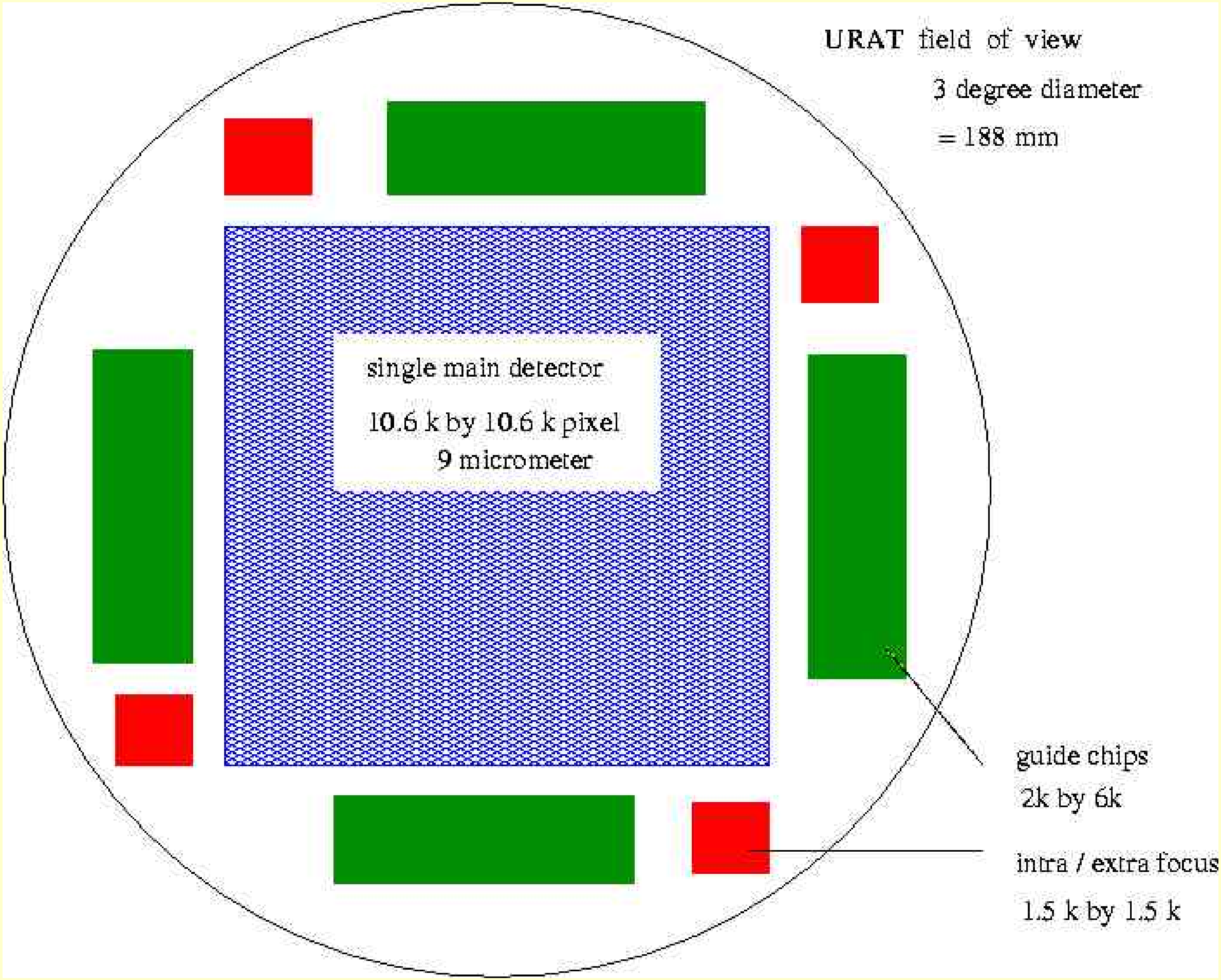
- 0.85 m aperture, f = 3.6 m telescope
- narrow bandpass (660-750 nm)
- stare mode, active guiding, long + short exposures
- 3 – 4 degree field of view
- large format detector (6in, 8in wafer)
- transportable, latitude adjustable (or 2 telescopes)
- optimized astrometric performance
- built on UCAC expertise and software

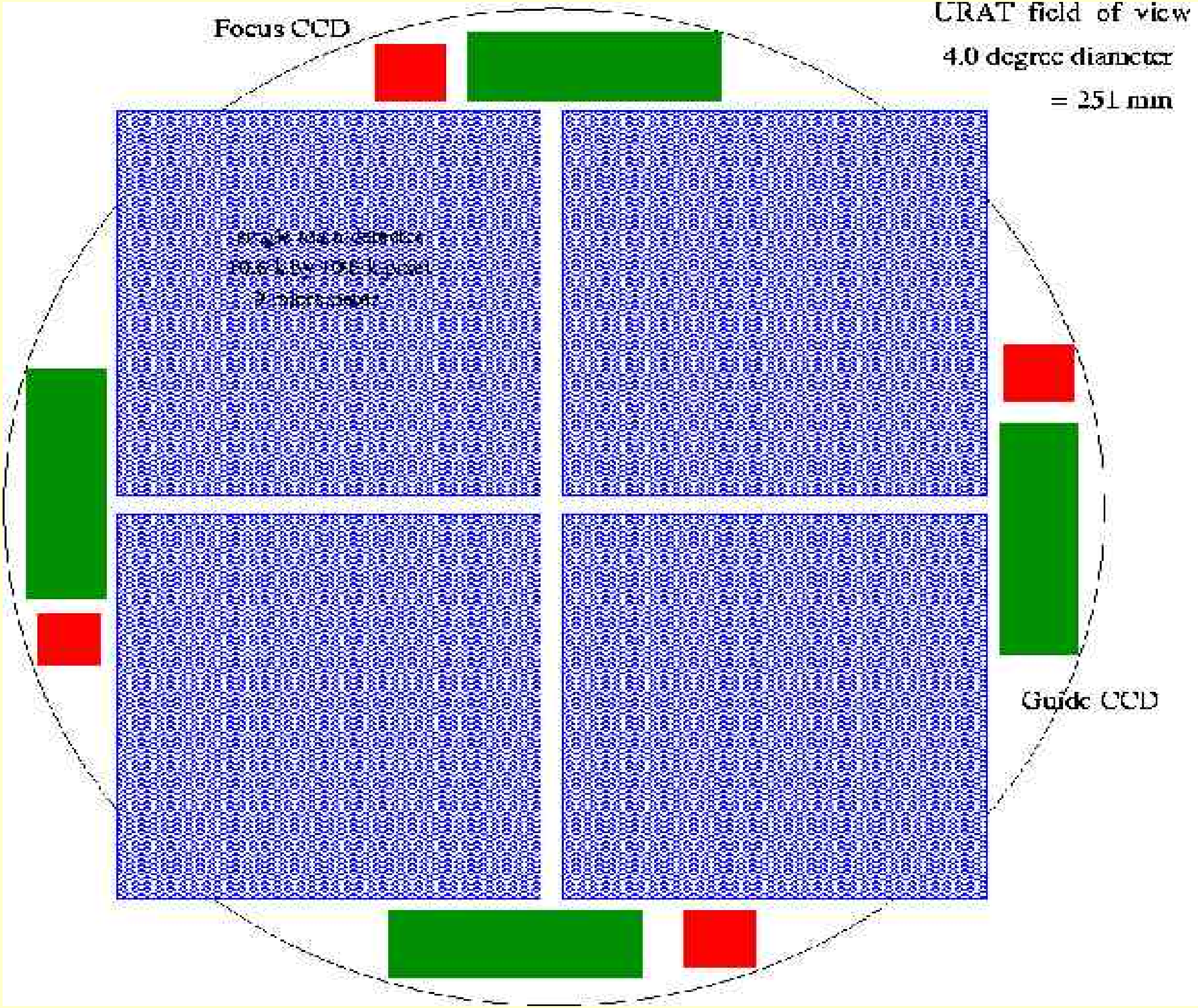
optical design solution



detector type

- LARGE monolithic chip
  - large area/chip has advantage for global astrometry
- CMOS
  - better properties than CCD but need R&D
- CCD SBIR program (2 vendors phase I study)
  - SBIR topic approved 2004
  - phase 1 concluded July 2005
  - STA selected: 95.4 mm, 10.6k pixel on a side
  - likely backside (high QE) + camera in phase 2


URAT field of view
3 degree diameter
= 188 mm
single main detector
10.6 k by 10.6 k pixel
9 micrometer
guide chips
2k by 6k
intra / extra focus
1.5 k by 1.5 k



URAT field of view
4.0 degree diameter
= 251 mm
Focus CCD
Guide CCD

data & reductions

- about 7 TB compressed pixel data / year / chip
- store on hard disks (RAID arrays)
  optional copy to tapes, DVDs
- recapitalize on UCAC experience
  (software pipeline exists already)
- dedicated calibration observations to solve for systematic errors (mas level)
- option for block-adjustment (global solution)
- direct tie to extragalactic reference frame

fundamental limits

- atmosphere:
  - about 10 mas (1-sigma, large FOV) for 30 ... 100 sec
  - more images (longer project time, more telescopes) can bring this random error down to few mas (maybe 1 mas)
- systematic errors:
  - 0.5 "/pixel, 9 µm pixel => 1/100 px = 5 mas = 90 nm
  - with effort and 'good astrometric hardware'
    1/200 px realistic = 2 to 3 mas

sites

- southern hemisphere:
  - Cerro Tololo (CTIO)
  - good experience, good infrastructure, available
  - excellent site (2400 hours / year for survey)
- northern hemisphere:
  - is a problem !
  - NOFS / Arizona: throughput = 1/2 CTIO
  - Canary Islands ? Hawaii? Baja California (Mexico) ?

schedule

- telescope
  - construction time about 2 years
  - long lead item: optics
  - blanks (6 months), polishing (9 months)
- detector & camera
  - acquisition about 2 years (CCD)
  - more R & D time for CMOS
- project
  - observing time 1 - 2 years per hemisphere
  - sequential with 1 telescope or parallel with 2

conclusions

- multiple sky overlaps: proper motions + parallax
- 0.6 m effective aperture, f= 3.6 m telescope
- astrometry: absolute on ICRS, 5 mas
- 10.6 k by 10.6 k single CCD or 4 of them
- software pipeline already exist (UCAC)
- about 5 million $US per telescope + detector
- 12 to 20 mag = regular survey
- 7 to 15 mag = extended survey (CCD + narrow filter)
- SBIR program for detector / camera “in good shape”
- need more money for optics / telescope

O rigins
B illions
S tar
S urvey

USNO study for
NASA roadmap (May 2005)

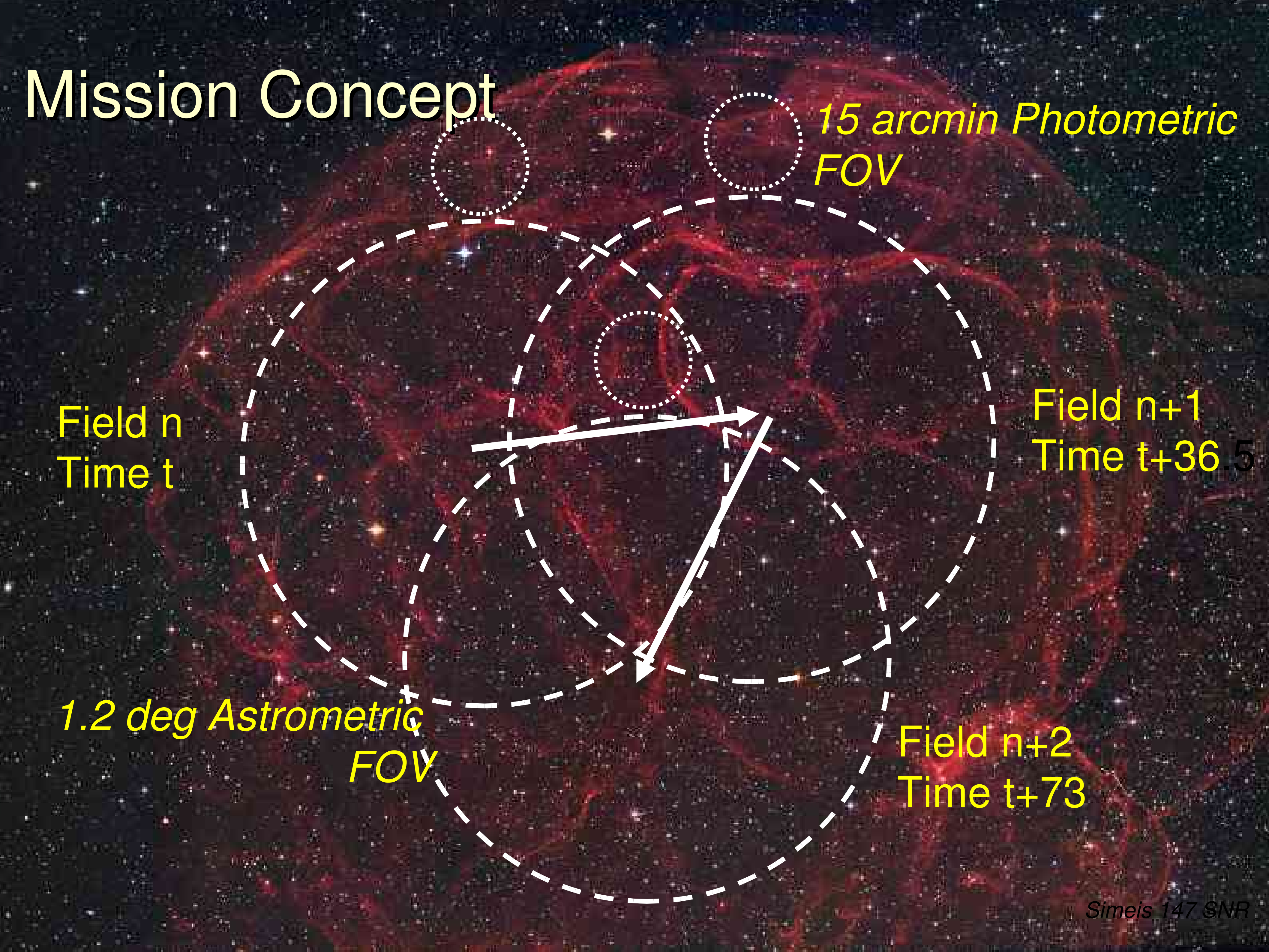
OBSS overview

- NASA's Origins roadmap study AO, 2004
- 'big' mission, $670M, similar to Gaia
- single aperture, stare-mode variant selected
- 1.5 m aperture, f= 50 m, 1.2 deg FOV
- launch 2014; flexible observing concept:
  - with Gaia: OBSS goes to 24th mag in selected areas
  - no Gaia: OBSS can do most of Gaia science
  - higher precision than Gaia, particularly at 20th mag
  - smaller number of visits/field than Gaia

OBSS operation

- general all sky survey (maybe 25% of time):
  - guided long + short exposure (1.5, 15 sec)
  - slew telescope by 0.5 deg + settle = 10 sec
- targeted fields (maybe 75% of time):
  - as required by science, can integrate long = deep
- absolute positions, motions, parallaxes:
  - utilize block adjustment technique (overl.fields)
  - link to extragalactic sources (galaxies, QSOs)
    --> need to go deep, else won't work !
  - frequent observation of dense calibration fields
- downlink 2-dim pixel data around objects

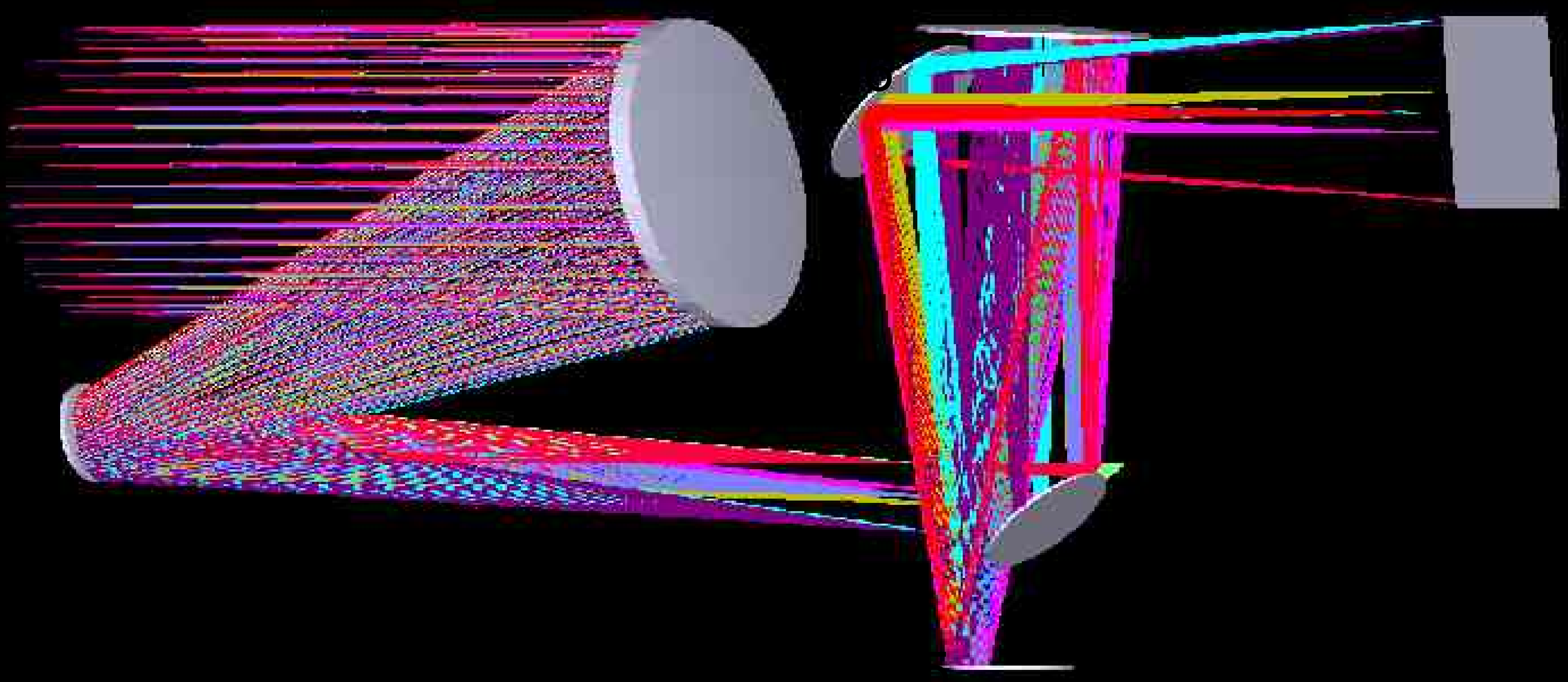
Mission Concept



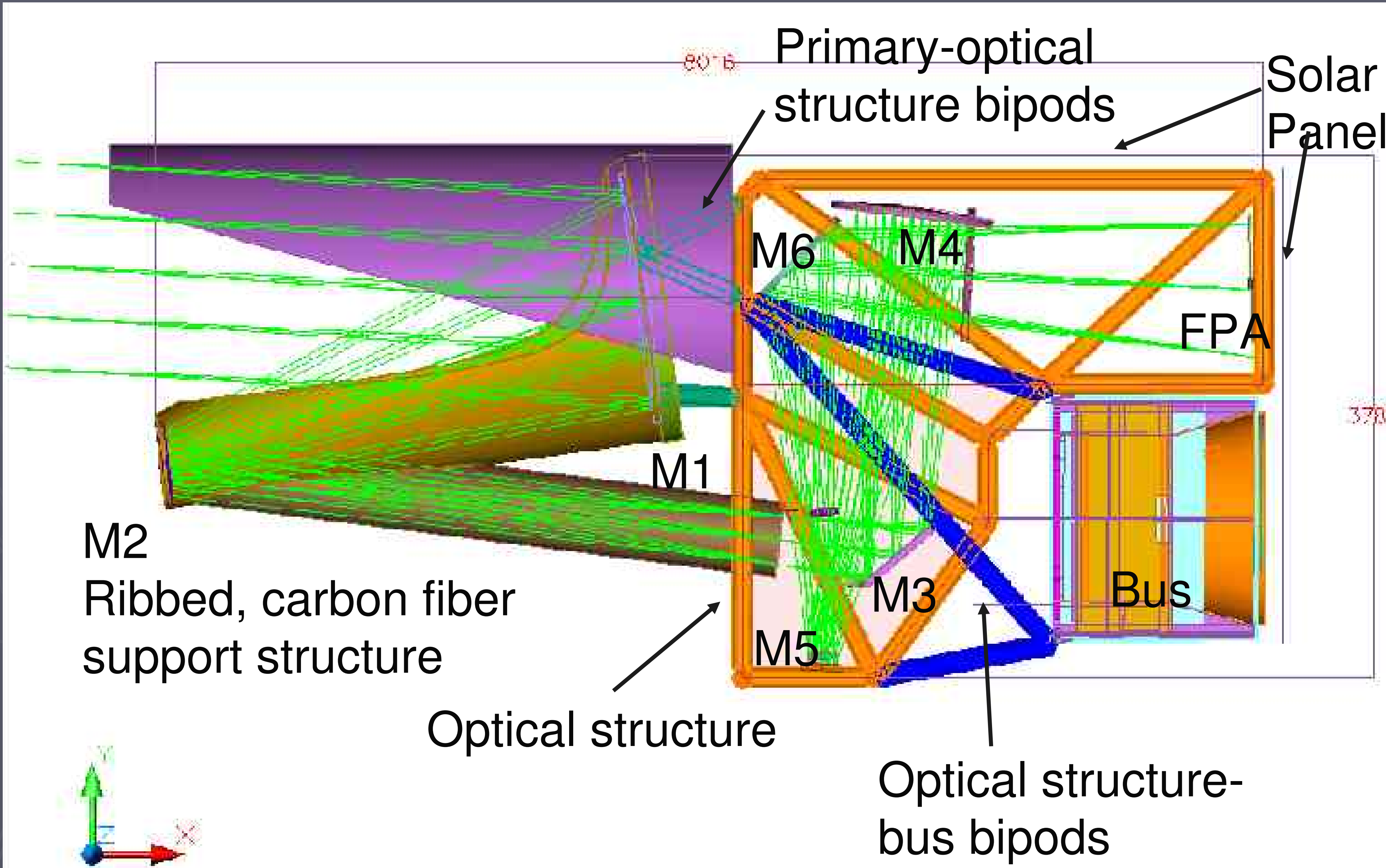
advantages over scanning mode

- simple design ---> cost savings
  - single aperture, no compound mirror
  - differential measures, no basic angle stability problem
  - buy larger focal plane instead: gain astrom.precision
- high gain steerable antenna possible
- flexible observing schedule
  - can hit 'interesting' fields more often
  - can be uniform all-sky, no scanning law restrictions
  - freq. observ. at high parallactic factor possible
- simultaneous high precision 2-dim observations

Optical Design



Optical Structure (1)



OBSS Optical Structure Design 2.0

OBSS focal plane

- 10 μm pixel size, 9 Gpx array
- readout in 10 sec
- V = 8.5 ... 21 mag dynamic range (2 expos.)
  - baseline: lateral anti-blooming CCDs
  - 5k by 5k chips
- sampling = 2 px / FWHM
- 360 CCDs (astrometry) in 1.2 deg circular FOV
- low res. spectrogr: 16-band color data

OBSS mission accuracy

(incl. assumed 5 μas RSS system.err.)

spec type	SMP μas	survey mode μas (n = 111)	targeted mode μas (n = 446)	V mag
M5	100	11	7	15
A0	153	13	8	
M5	246	24	13	18
A0	590	56	56	
M5	1000	95	48	21
A0	2400	230	114	

M illi

A rcsecond

P athfinder

S urvey

USNO micro-satellite proposal

Relevant MAPS Output

Star catalogs: Orders of magnitude improvement in accuracy and density,
Viable for decades

Detector demonstration:
Demonstrate and characterize performance on-orbit ,
Pathfinder for CMOS star tracker

Operational demonstration:
Pathfinder for OBSS,
micro-satellite technology
astrometric limits
reduction principles

MAPS overview

- 15 cm, single aperture, 1.1 degree FOV
- step-and-stare mode of observation
- single, large-format detector, overlapping fields of view
- CMOS or CMOS-hybrid chip, 8k by 8k
- 3 to 14 mag, regular survey
- deeper around extragalactic sources, longer integr.time
- 1 to 3 year operation
- 1 mas positions
- time from funding to launch: 2 years

MAPS: Primary Objective

- Astrometric microsatelite
- Mission: measure positions of brightest ~10 million stars to better than 1 mas accuracy
- Using ~15—20 year baseline to *Hipparcos*, reduce proper motion errors to < 100 microarcseconds for MAPS-*Hipparcos* stars (110,00 stars)
- Resultant star catalogs:
  - Better than 1 milliarcsecond accuracy
  - 100x density of *Hipparcos* catalog
  - 110,000 bright star positions viable for decades

MAPS Status

- Initial feasibility analysis completed
- Team:
  - PI: USNO
  - Payload Integration: NRL
    - Optics: SSG
    - Focal Plane: NASA/GSFC
  - Bus: AeroAstro
- Estimated cost = $40M
- $300k for Phase-A study: promising options

thanks ...

URAT :

Uwe Laux, Tautenburg (optical design)
Andrew Rakich, EOS Technologies (optical design)

OBSS / MAPS :

entire teams, in particular Bryan Dorland
SSG Tinsley, E2V, JPL

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