Concise telescope pointing algorithm

using IAU 2000 precepts

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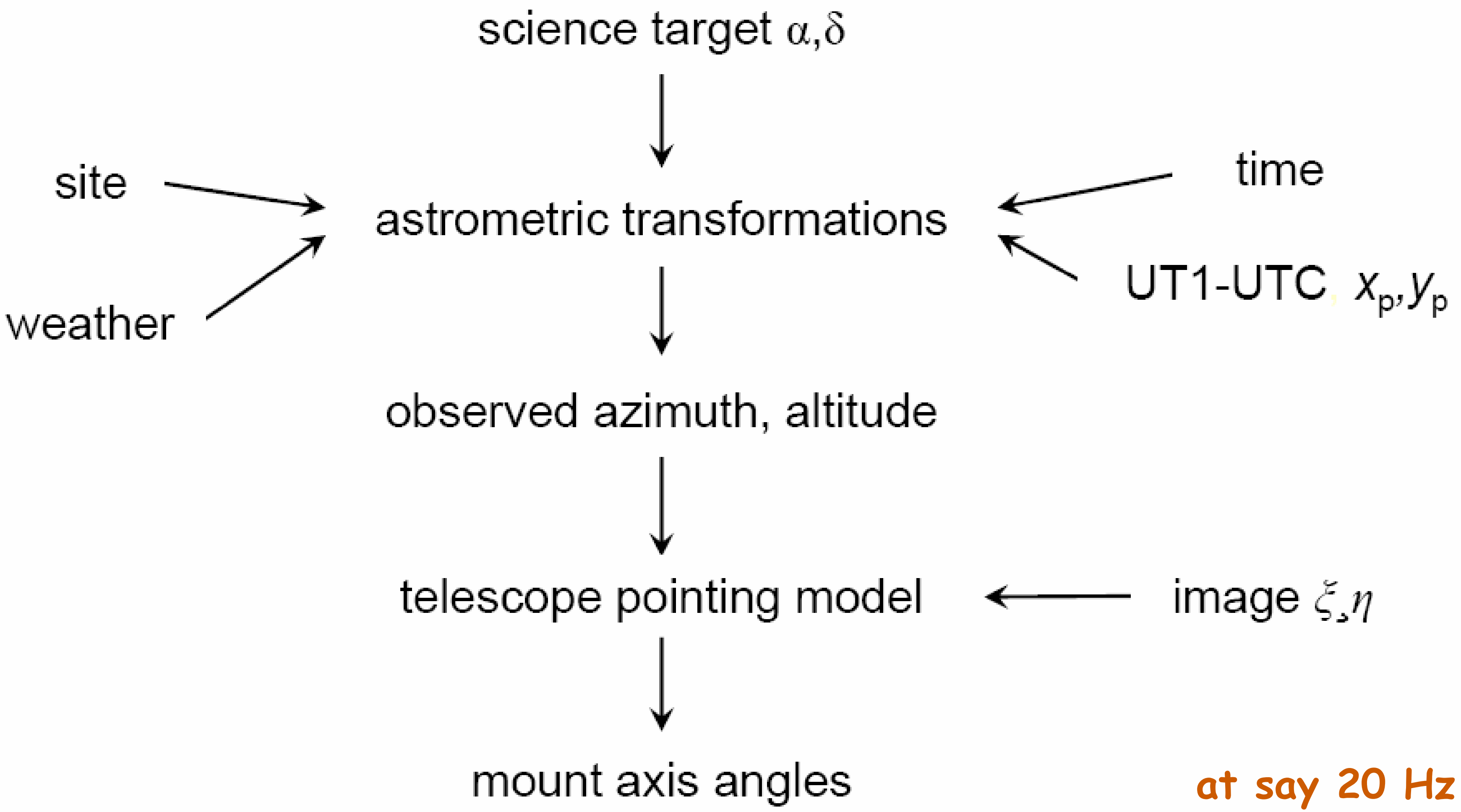
TCS basics

- The TCS is there to orient the mount axes so that the telescope sees a specified celestial target.
  - Initial alignment (acquisition) is called "pointing"
  - Maintaining the alignment is called "tracking"

- The target-to-mount calculation has two parts:
  - Astrometric transformations
  - Telescope-specific pointing model

Target to mount



at say 20 Hz

Astrometric transformations

CATALOG [α,δ]

proper motion, catalog epoch to J2000

INTERNATIONAL CELESTIAL REFERENCE SYSTEM [α,δ], epoch J2000

proper motion, J2000 to date

BARYCENTRIC CELESTIAL REFERENCE SYSTEM [α,δ] of date

annual parallax

ASTROMETRIC [α,δ]

light deflection
annual aberration

GEOCENTRIC CELESTIAL REFERENCE SYSTEM [α,δ]

frame bias
precession
nutation

CELESTIAL INTERMEDIATE REFERENCE SYSTEM [α,δ]

Earth rotation

TERRESTRIAL INTERMEDIATE REFERENCE SYSTEM [λ,φ]

polar motion

INTERNATIONAL TERRESTRIAL REFERENCE SYSTEM [λ,φ]

site longitude
diurnal aberration and parallax

TOPOCENTRIC [h,δ]

equatorial to horizon

TOPOCENTRIC [A,E]

refraction

OBSERVED [A,E]

Accuracy versus costs

- **Why not implement the transformations rigorously and in full?**
  - You can, and, on big no-compromise telescopes with hefty computer resources, you should.
  - But the latest IAU models are *thousands* of terms long. At some level this is plain wasteful, especially if your TCS is a microprocessor.

- **What economies are possible?**
  - Use simplified models.
  - Neglect small effects altogether.

What accuracy to aim for?

- No telescope currently in existence will reach 1" RMS consistently in operation.
  - Few are even 5".
  - The best amateur telescopes maybe 20".

- How much operational hassle is acceptable?
  - Polar motion?
  - Precision weather readings?

- How fast do you want to go?
  - A sufficiently concise model can be run at servo rates.

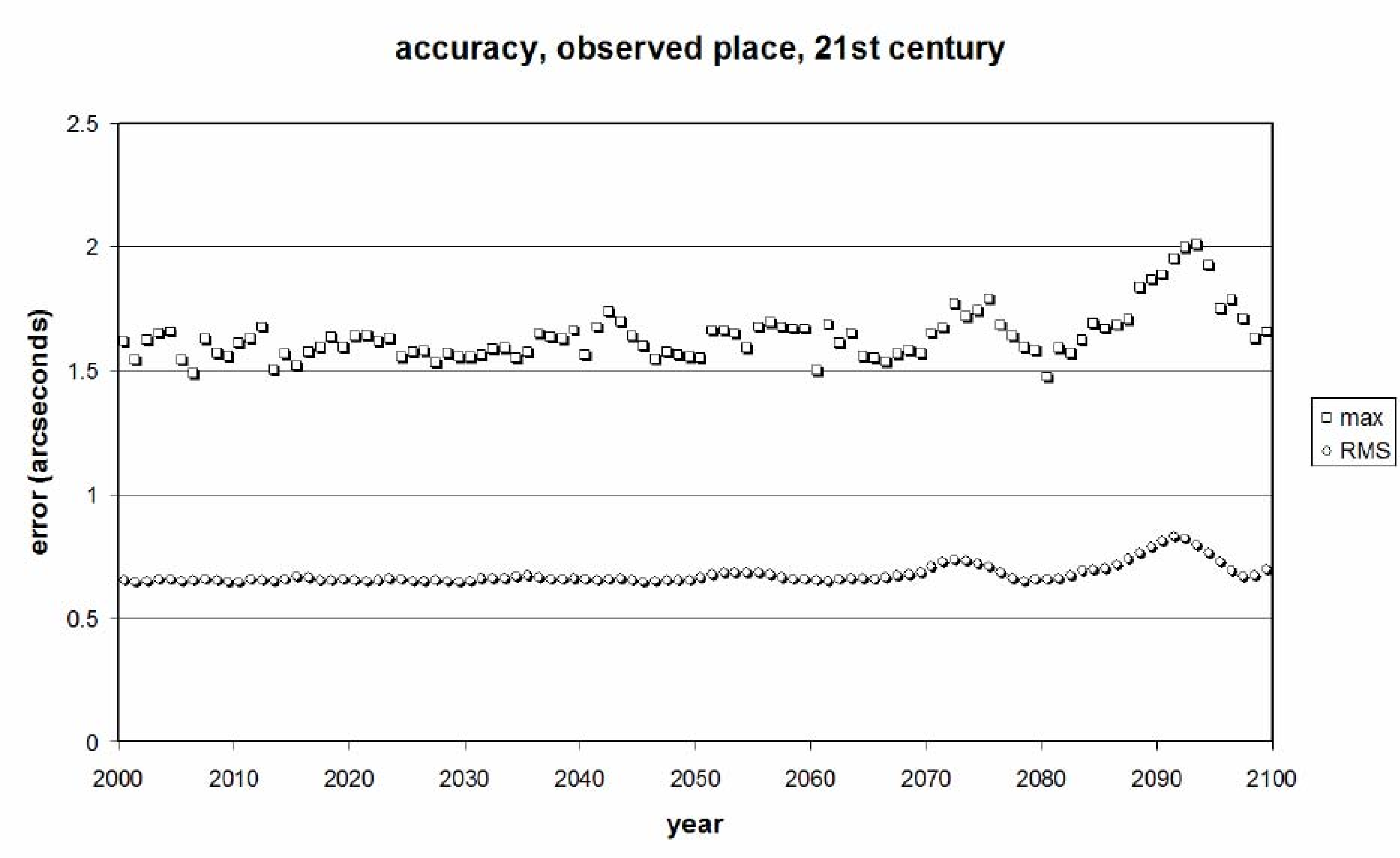
A good balance: 2"

- You can leave out:
  - Parallax (<1")
  - Light deflection (~1 mas)
  - Frame bias (~25 mas)
  - Motion of RA origin (<0.1")
  - Aberration E-terms (~0.3")
- …but you must include:
  - Annual aberration (~20")
  - Precession (tens of arcsec per year)
  - Nutation (~10")
  - Earth rotation (that's what makes tracking happen)
  - UT1–UTC (~10" now, unlimited in the future)
  - Refraction (tens of arcsec)
- …and it's best not to neglect:
  - Proper motion (do it at target look-up)
  - Pressure and temperature variations

C code for astrometric part

```
t = ut-51544.5;                          /* days since J2000.0 */

w = 4.895+1.72021e-2*t;                  /* aberration */
xa = cos(rc)*cos(dc)+0.99e-4*sin(w);
ya = sin(rc)*cos(dc)-0.91e-4*cos(w);
za = sin(dc)-0.40e-4*cos(w);

w = 2.182-9.242e-4*t;                    /* precession-nutation */
x = 2.66e-7*t-33.2e-6*sin(w);
y = -8.14e-14*t*t+44.6e-6*cos(w);
z = 1.0-x*x/2.0;
xb = z*xa-x*za;
yb = ya-y*za;
zb = z*za+x*xa+y*ya;

w = 4.8949612+6.300387486755*t;          /* Earth rotation */
xa = xb*cos(w)+yb*sin(w);
ya = -xb*sin(w)+yb*cos(w);

xb = xa*sin(phi)-zb*cos(phi);            /* to altaz */
zb = xa*cos(phi)+zb*sin(phi);

zb += 2.77e-7*p/zb;                      /* refraction */
```

Astrometric performance



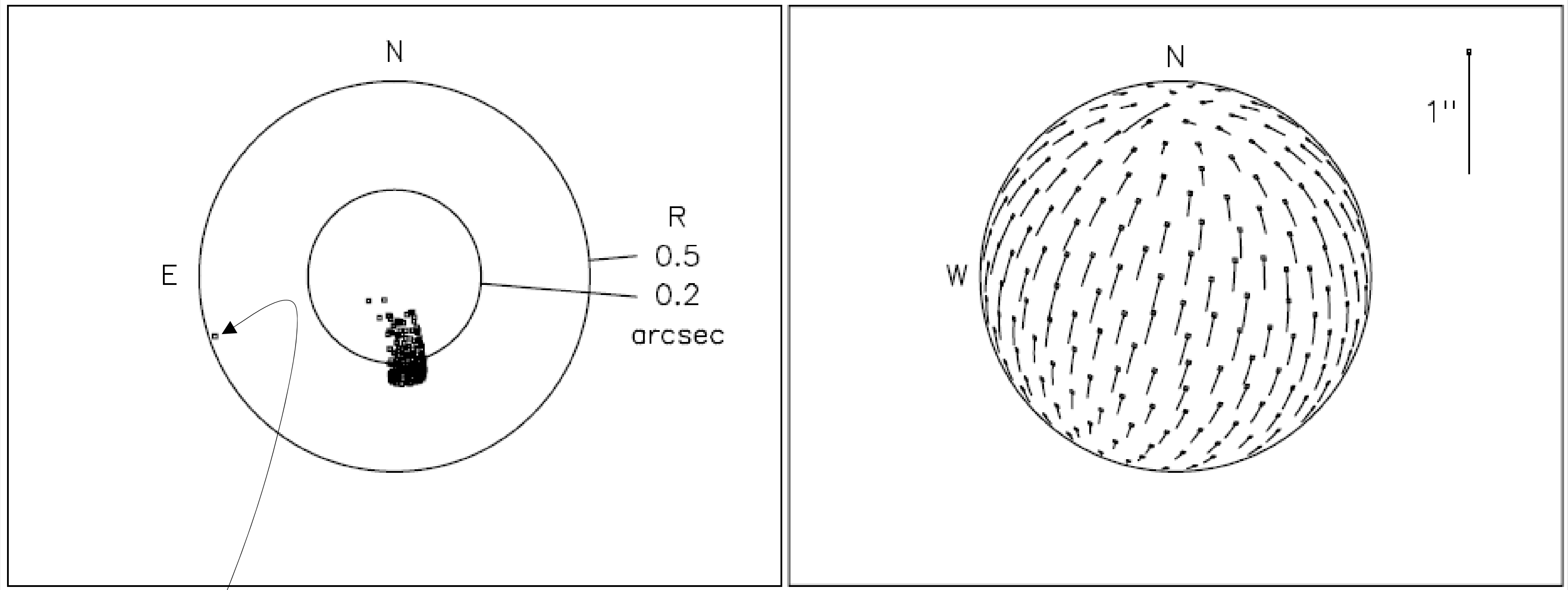
Pointing model

equatorial	*altazimuth*	
-IH	IA	roll index error
ID	IE	pitch index error
-NP	NPAE	roll/pitch nonperpendicularity
-CH	CA	OTA/pitch nonperpendicularity
ME	AN	roll axis meridional misalignment
-MA	AW	roll axis transverse misalignment
TF	TF	Hooke's-Law vertical flexure

C code for pointing model (altaz)

```c
w = sqrt(xb*xb+ya*ya+zb*zb);           /* renormalize */
xb /= w; yb = ya/w; zb /= w;

xa = xb-pf*zb*xb;                      /* flexure */
ya = yb-pf*zb*yb;
za = zb+pf*(xb*xb+yb*yb);

xb = xa+px*za;                         /* tilt */
yb = ya+py*za;
zb = za-px*xa-py*ya;

w = (pc+pn*zb)/sqrt(xb*xb+yb*yb);      /* non-perpendicularities */
xa = xb+w*(yb-w*xb);
ya = yb-w*(xb+w*yb);

w = fmod(atan2(ya,-xa)+pa,D2PI);       /* index errors */
a = w >= 0 ? w : w+D2PI;
e = atan2(zb,sqrt(xa*xa+ya*ya))-pb;
```

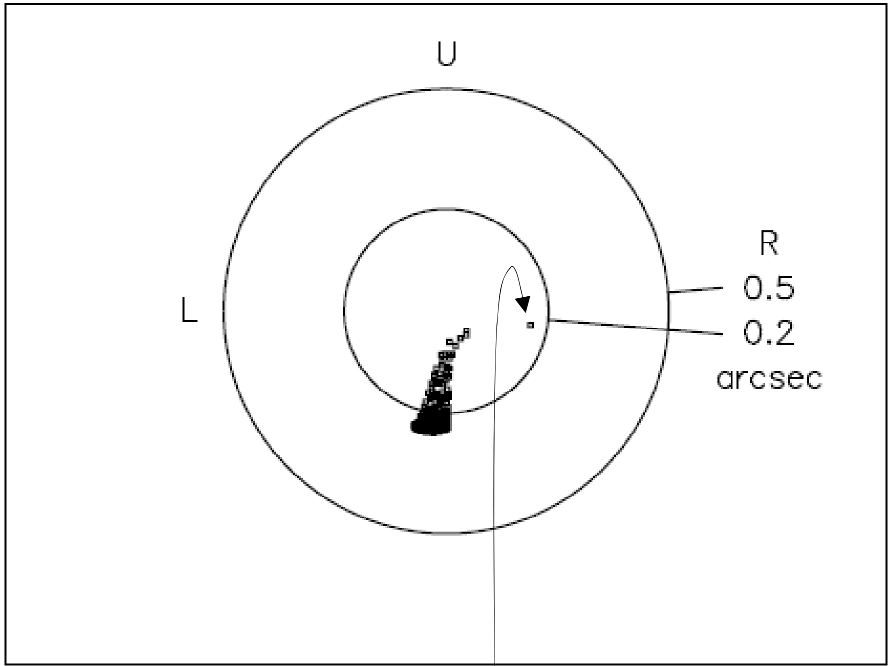
Pointing model performance (equ)

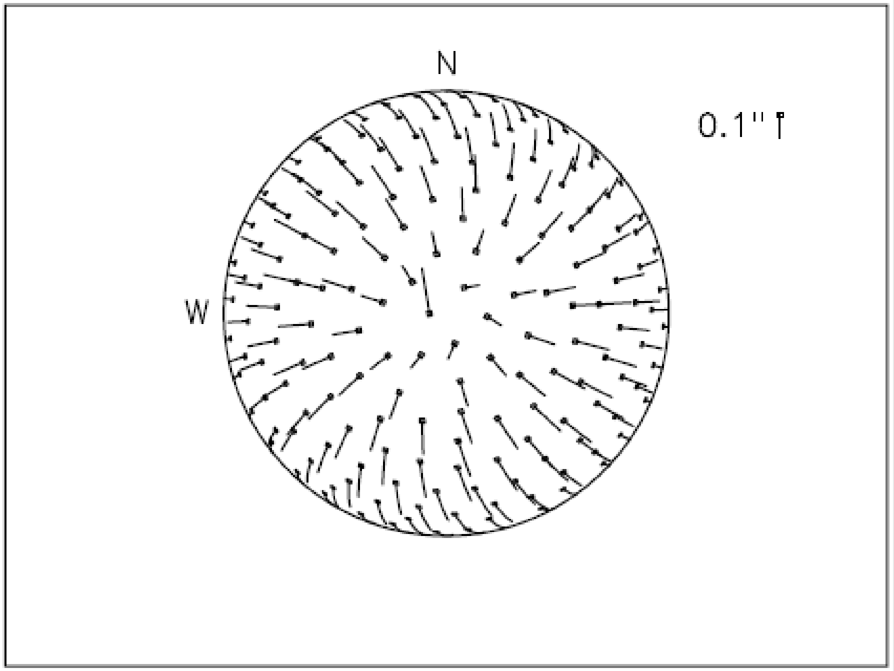


δ = 86.9°

IH	+350″
ID	+300″
NP	+250″
CH	+200″
ME	+150″
MA	+100″
TF	+50″

Pointing model performance (altaz)





$\zeta = 4.3°$

IA	+350″
IE	+300″
NPAE	+250″
CA	+200″
AN	+150″
AW	+100″
TF	+50″

How IAU 2000 helps

- **Clean separation between Earth spin and pole orientation:**
  - Earth Rotation Angle is simply a+b*UT
  - No sidereal time (which is ERA + precession)
  - No equation of the equinoxes (nutation part of ST)
  - Precession is just polynomials for pole X and Y
- **New RA zero point (the CIO):**
  - Practically stationary at $\alpha_{2000} = 0$

Result: $(\alpha,\delta)_{ICRS} \rightarrow (h,\delta)$ accurate to ~**1**″ using a total of **13** coefficients

End