Radar Pointing Calibration using the Sun

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Pointing: Why does it matter?

- Weather radars: Spatial mapping of weather echos
- Cloud radars: Doppler velocity
  Ice hydrometeors fallspeed: ~1m/s
  Vertical Fallspeed bias due to horizontal wind (15m/s, 1º mispointing):
  cos(89º) * 15m/s = 26cm/s
- All kind of multi radar analysis: Requires precise beam volume matching

We require a calibration target...

Our Motivation

- There is (to our knowledge) no generic, open source tool available for radar pointing analysis and calibration
- Can we do “active” pointing correction of a scanning radar? That means, correcting all misalignments just based on Software?

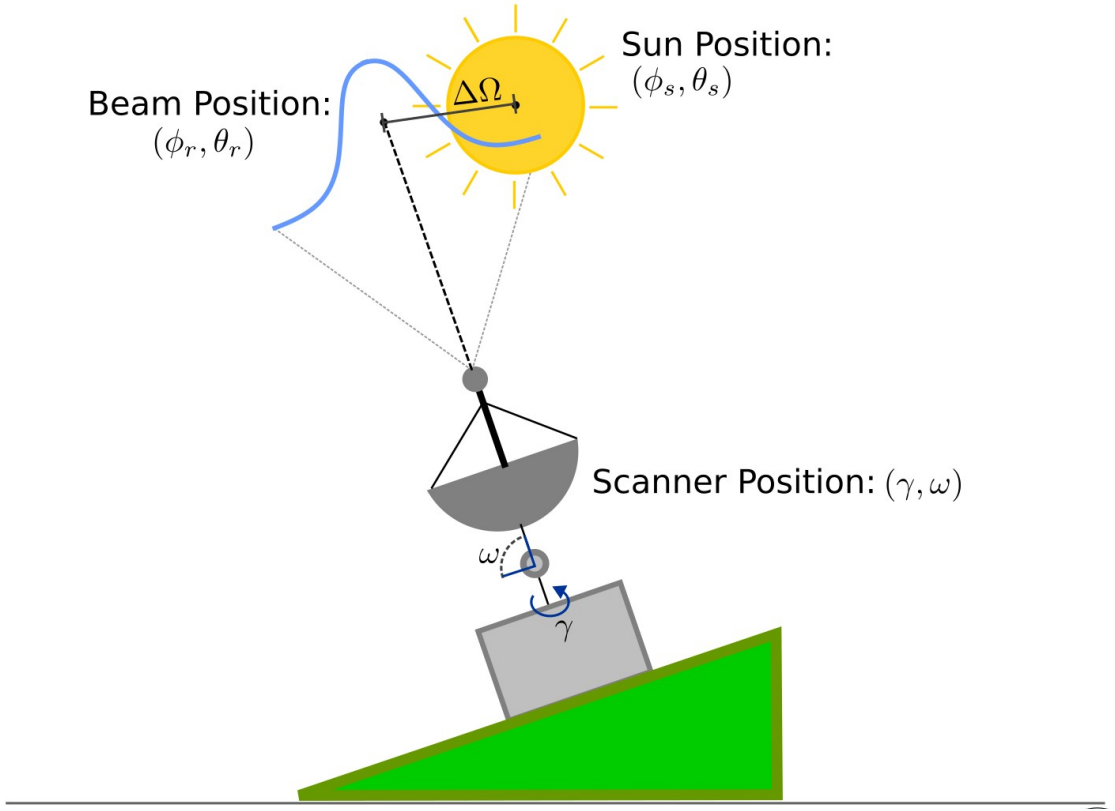
Outline Today

1) Paul: Ideas and Theory

2) Gregor: Actual Sun scan and Python Tutorials

The Idea

Estimate local mispointing based on a single sunscan (1)

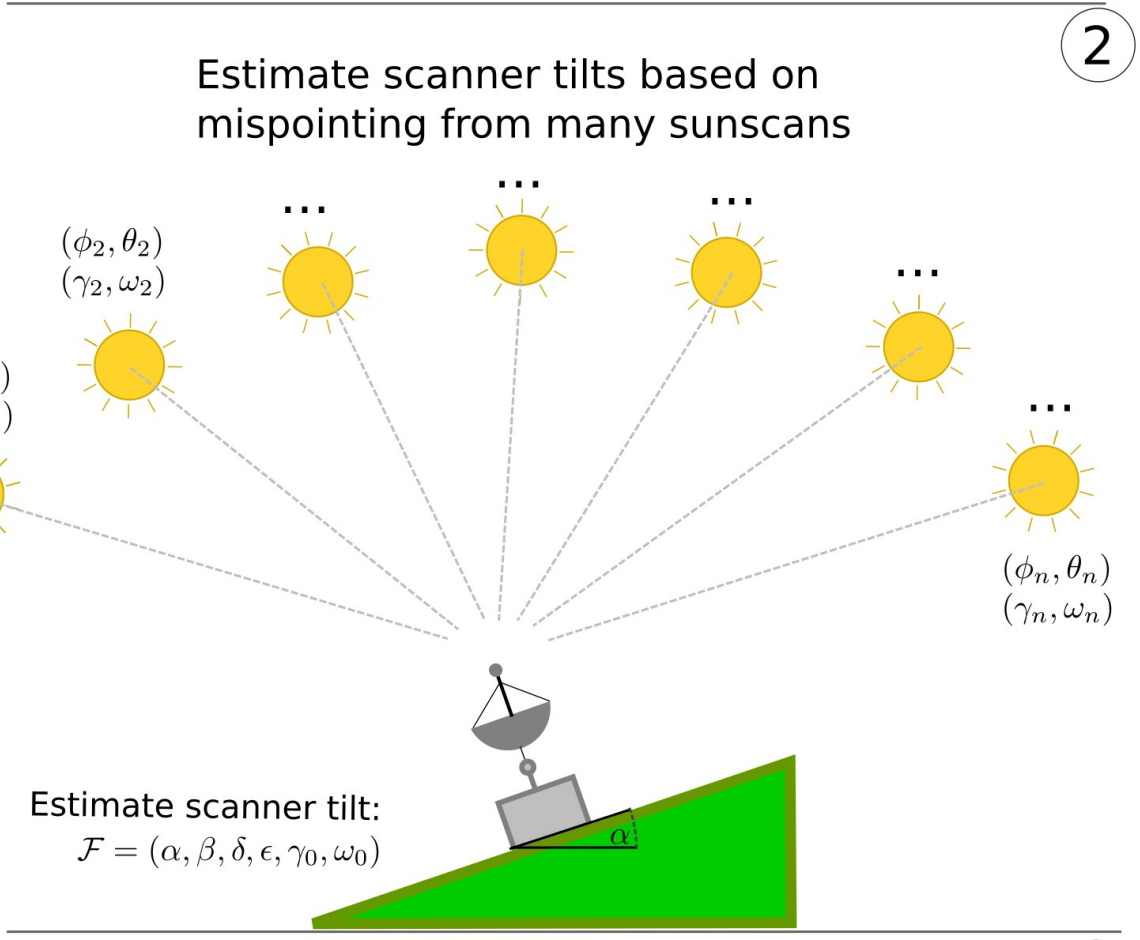


Sky: ϕ, θ

Scanner: γ, ω

$$M_{\mathcal{P}}(\gamma, \omega) = \phi, \theta$$

The Idea

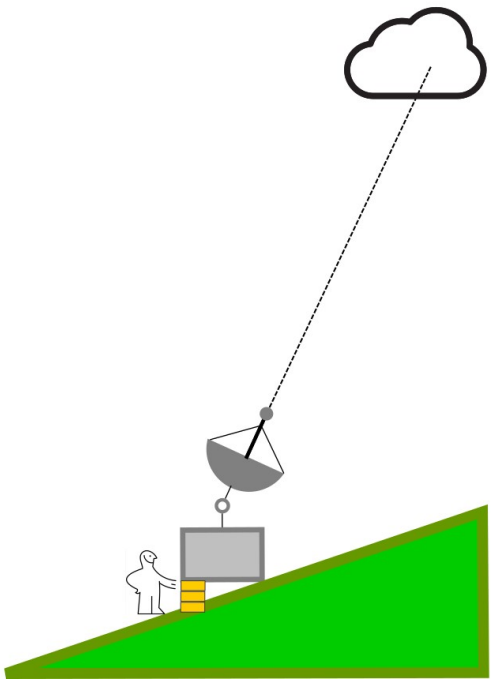

2
Estimate scanner tilts based on
mispointing from many sunscans
(ϕ_1, θ_1)
(γ_1, ω_1)
(ϕ_2, θ_2)
(γ_2, ω_2)
(ϕ_n, θ_n)
(γ_n, ω_n)
Estimate scanner tilt:
$\mathcal{F} = (\alpha, \beta, \delta, \epsilon, \gamma_0, \omega_0)$
α

The Idea

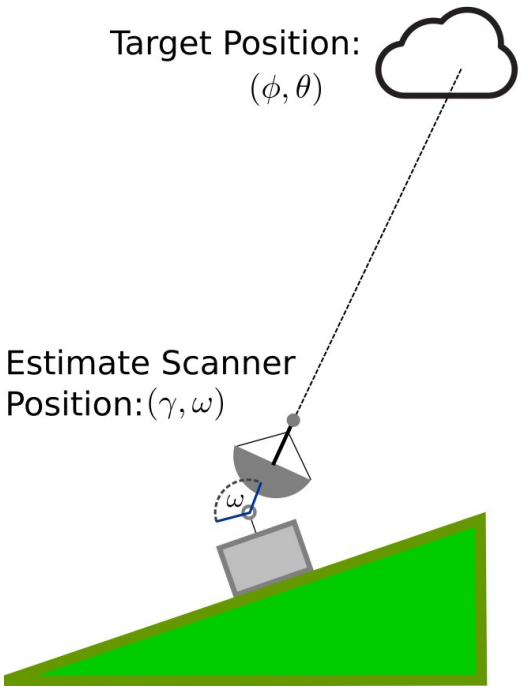
Correct for scanner tilt

3

a) Mechanically



b) by Software

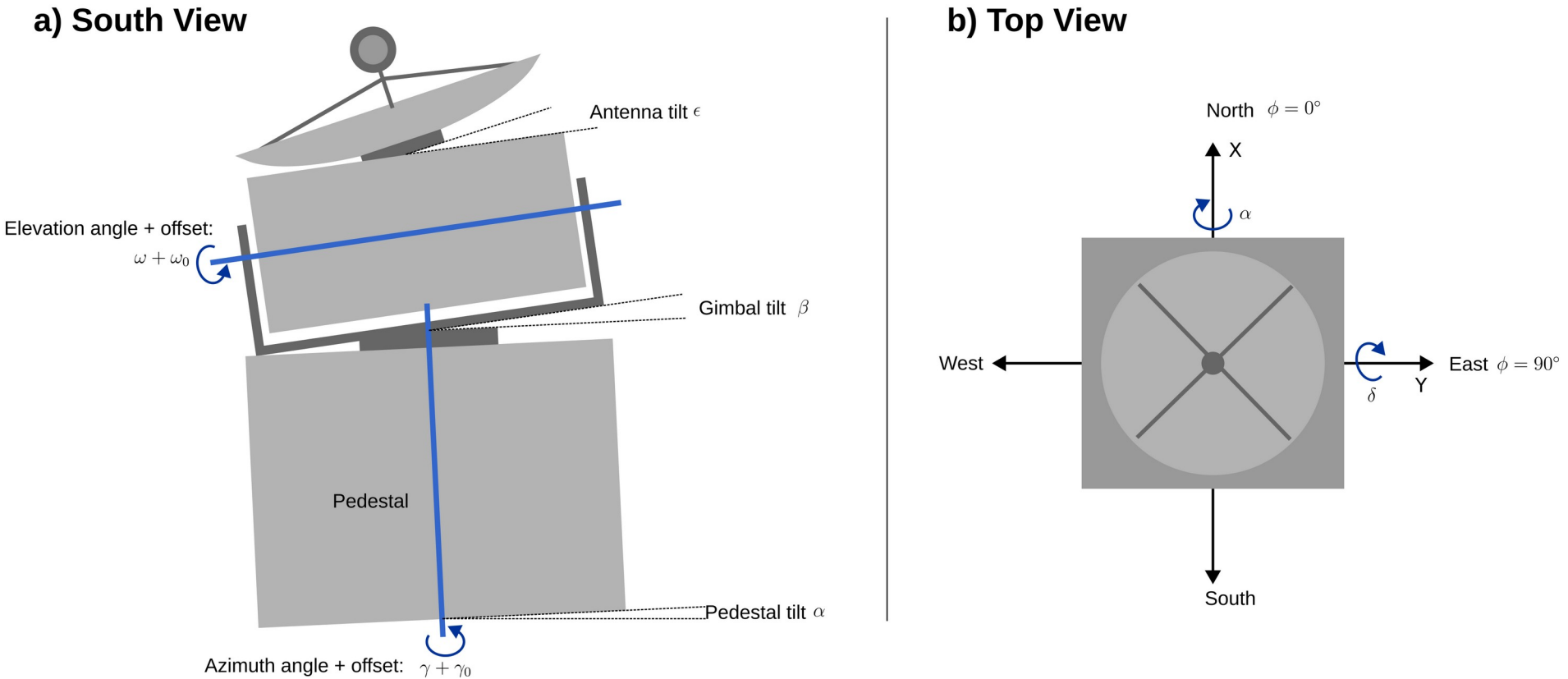


Dynamic Inaccuracies

- Azimuth backlash b_γ: Mispointing depends on the **direction** of movement
- Time offset t_0 between signal recording and axis encoders: Mispointing depends on the **speed** of movement

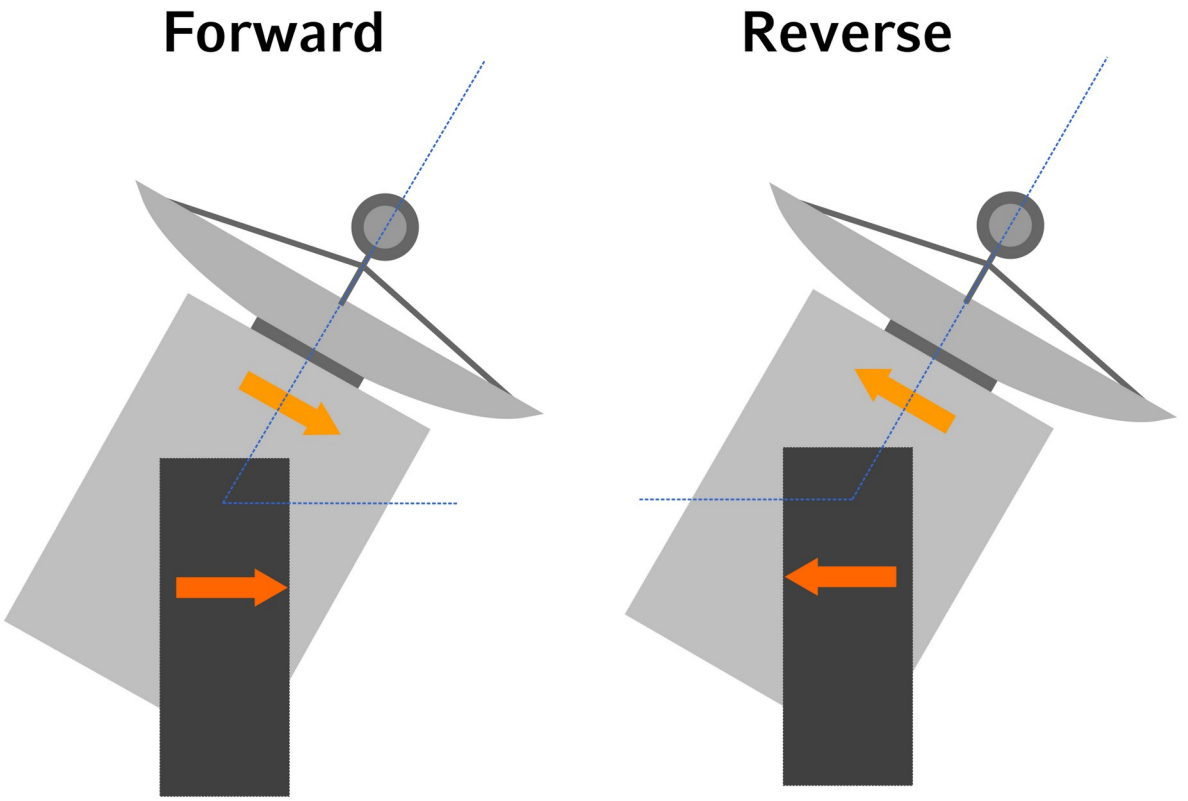
$$\tilde{\gamma} = \gamma + b_\gamma \mathrm{sign}(\gamma_v) + t_0 \gamma_v \qquad \tilde{\omega} = \omega + t_0 \omega_v$$

Scanner Inaccuracies



Elastic elevation offset: $\omega_{\text{flex}} = \chi \cos(\omega)$

Trick: Overhead Scan



$$\gamma' = \gamma + 180^\circ, \qquad \omega' = 180^\circ - \omega.$$

Some myths about Sun scans

- We require a sunny day

  → No! Similar to the radar being able to penetrate multiple cloud layers, the sun signal is visible even if hidden behind clouds

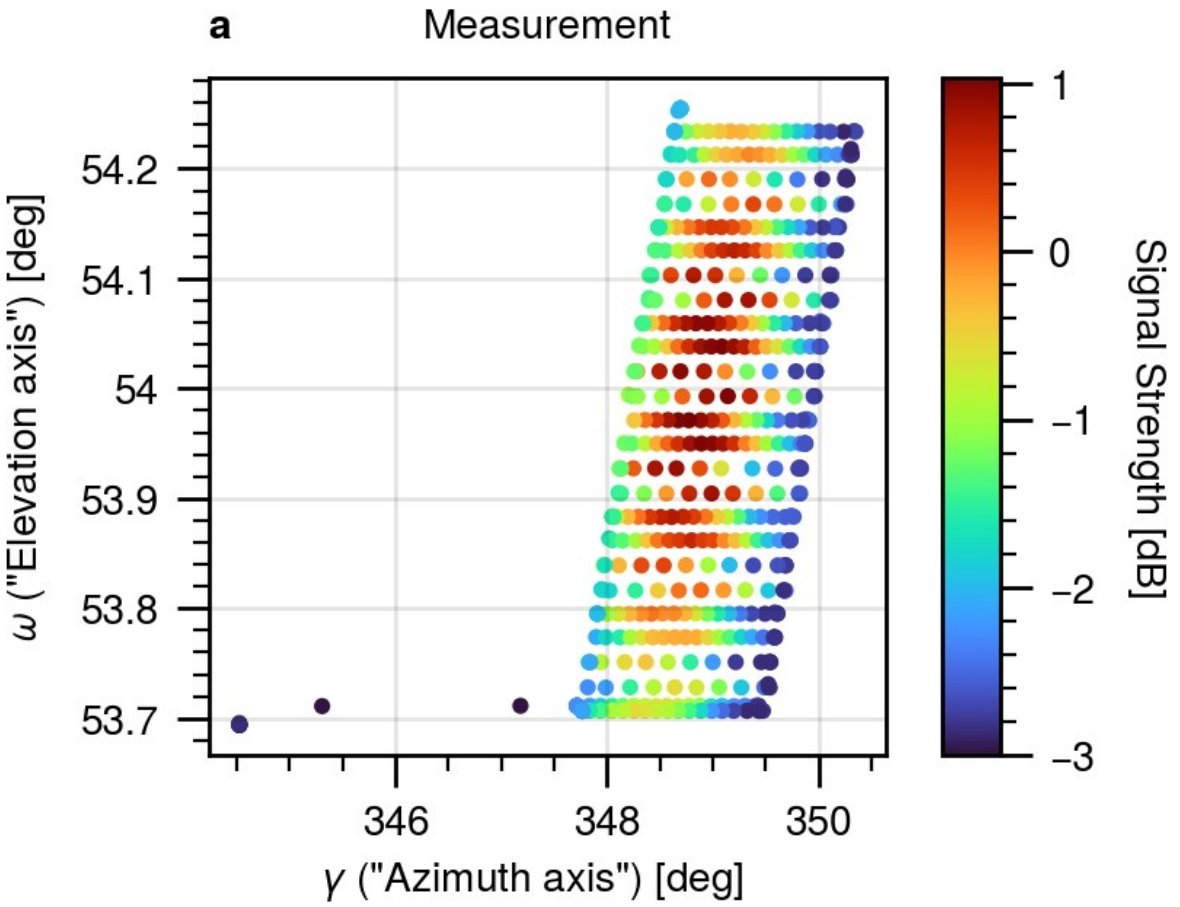
- We need to turn off the radar transmitter to “hear” the weak sun signal

  → No! Just select the cloud free sections along the beam after measuring (usually, the far range gates are well suited)

Bottom line: Just scan!

(maybe lower your averaging time a bit, we use 0.3 s)

Example Sun Scan



Requirements for a good scan:

- The sun must be visible somewhere…
- Use two different azimuth velocities
- Have at least one sky-only sample for calibration

Not important: The actual scan pattern!
It's just a bunch of points with: time, azimuth, elevation, signal
$(t_i, \gamma_i, \omega_i, S_i)$

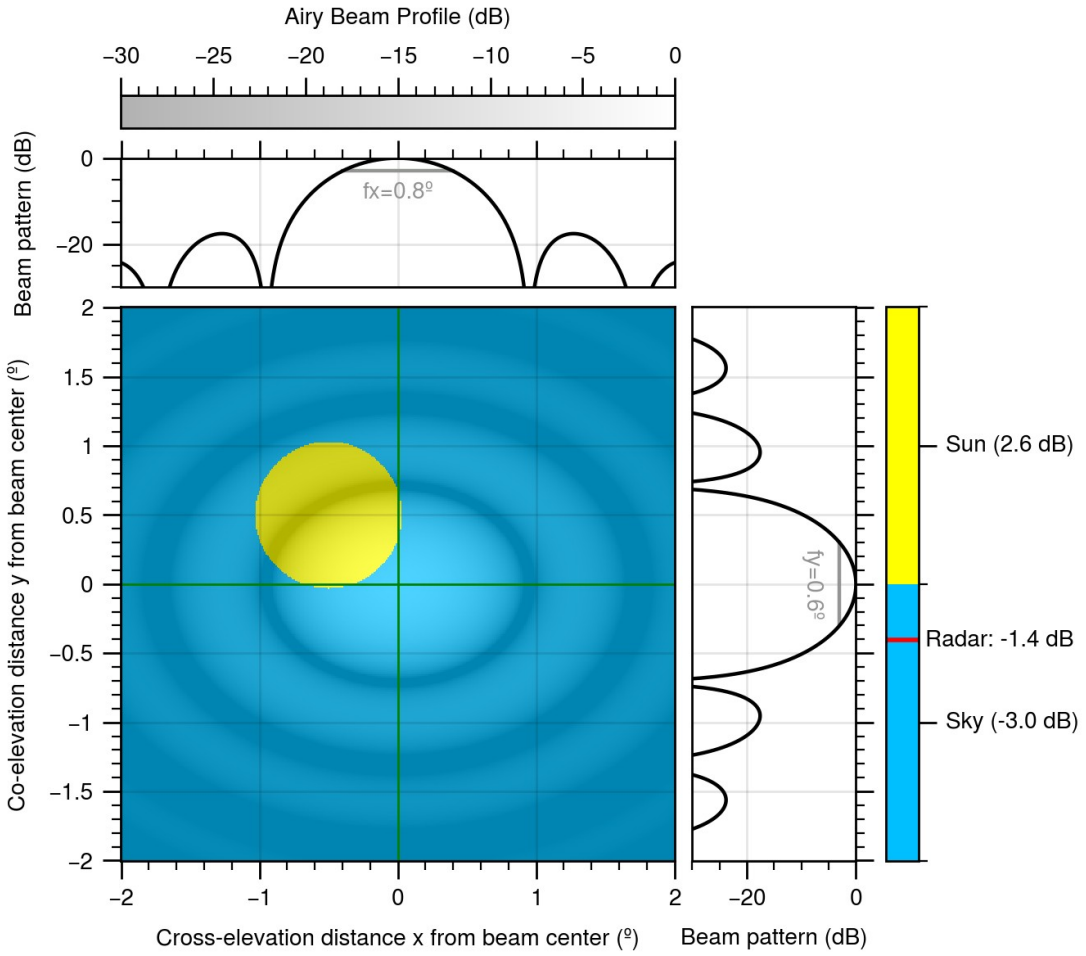
Sun Scan Simulation

Signal=Antenna pattern * Sun disk

Antenna pattern: “Airy” pattern, based on first order Bessel function:

$$G(x,y) = G_0 \left(\frac{2J_1(r)}{r} \right)^2, \qquad r = \sqrt{\left(\frac{x}{x_0} \right)^2 + \left(\frac{y}{y_0} \right)^2}$$

How a Radar Sees the Sky



Sun and Sky Brightness

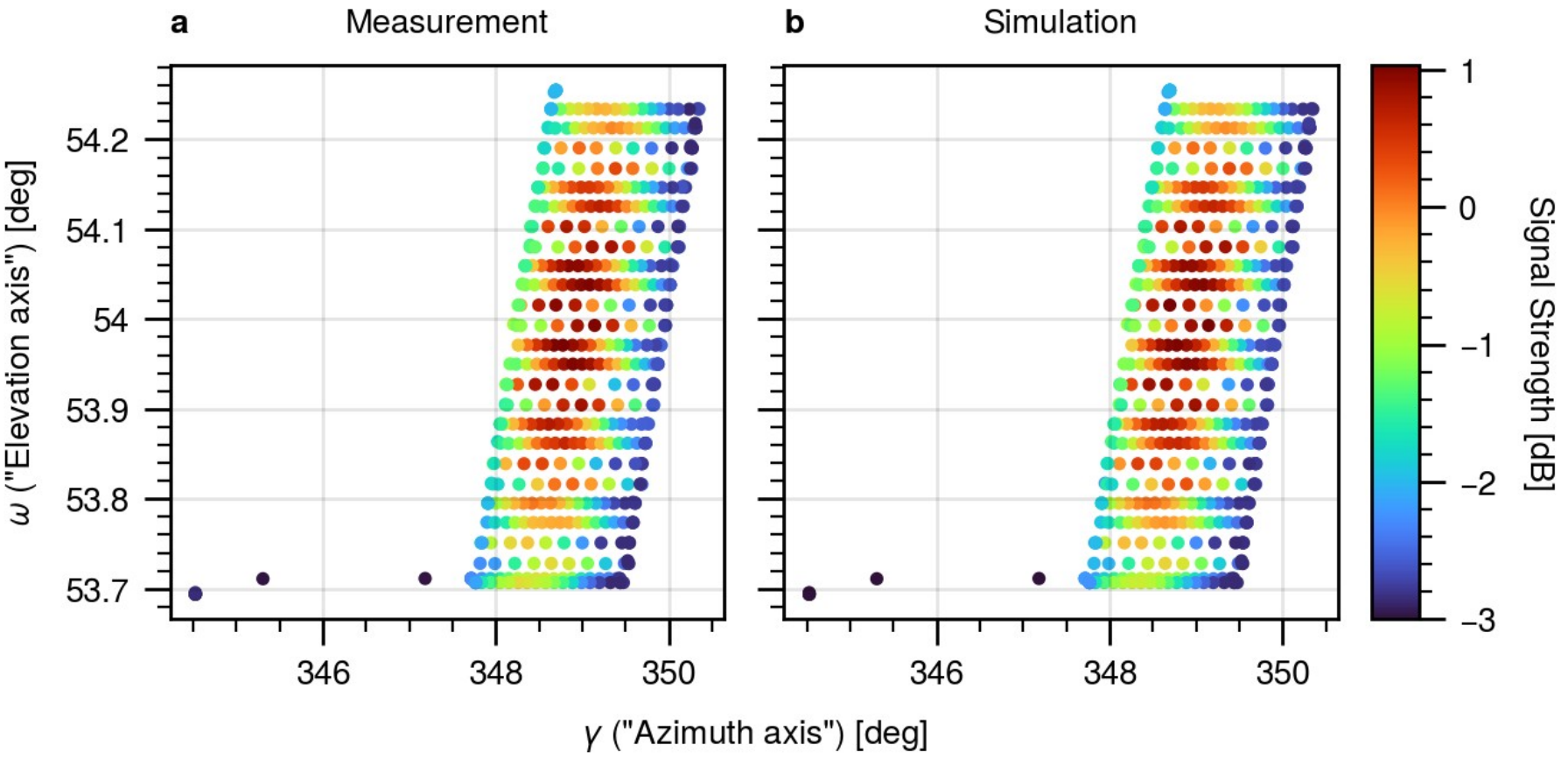
Signal Q:

$$Q = H * G = H_0 \int_{\text{sky}} G(x,y)\,dx\,dy \;+\; H_1 \int_{\text{sundisk}} G(x,y)\,dx\,dy.$$

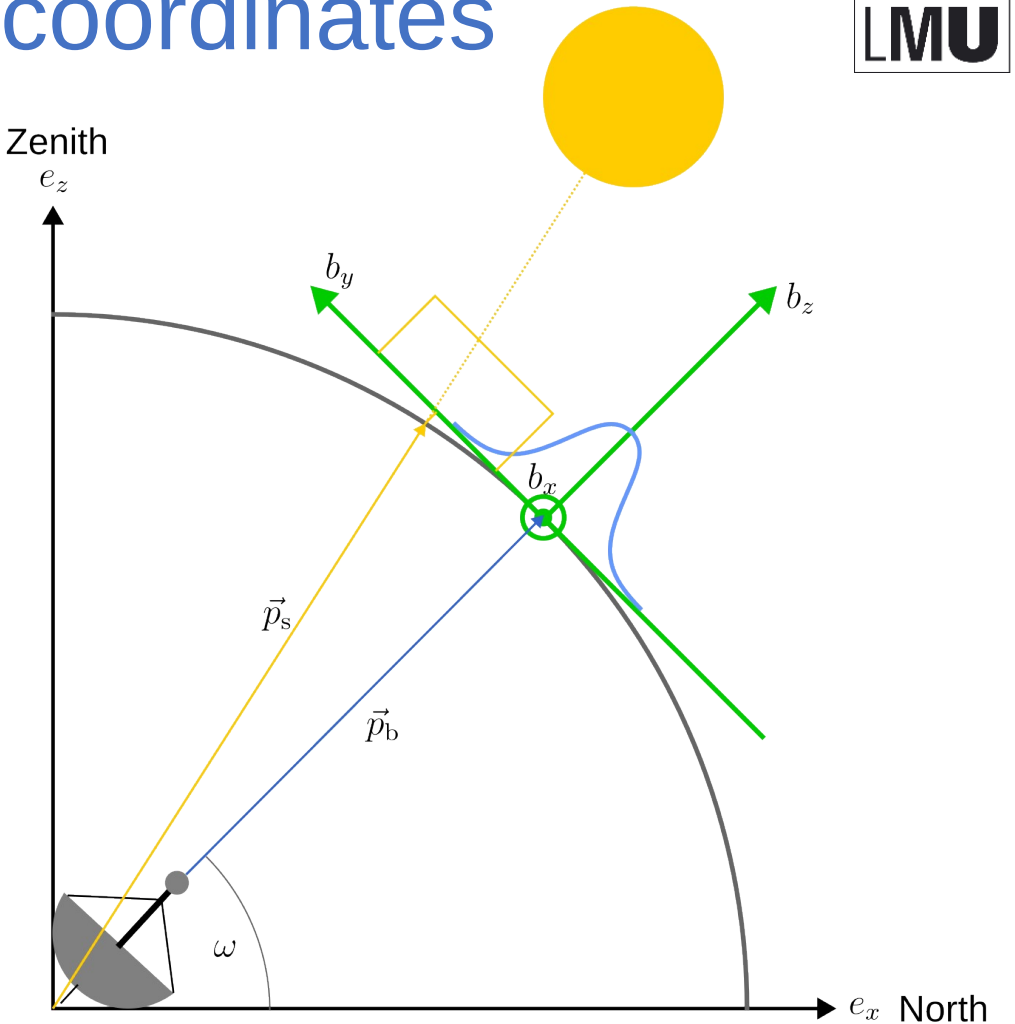
Sky brightness H0: Can be directly measured

Sun brightness H1: Estimated based on maximum signal strength of Sun scan

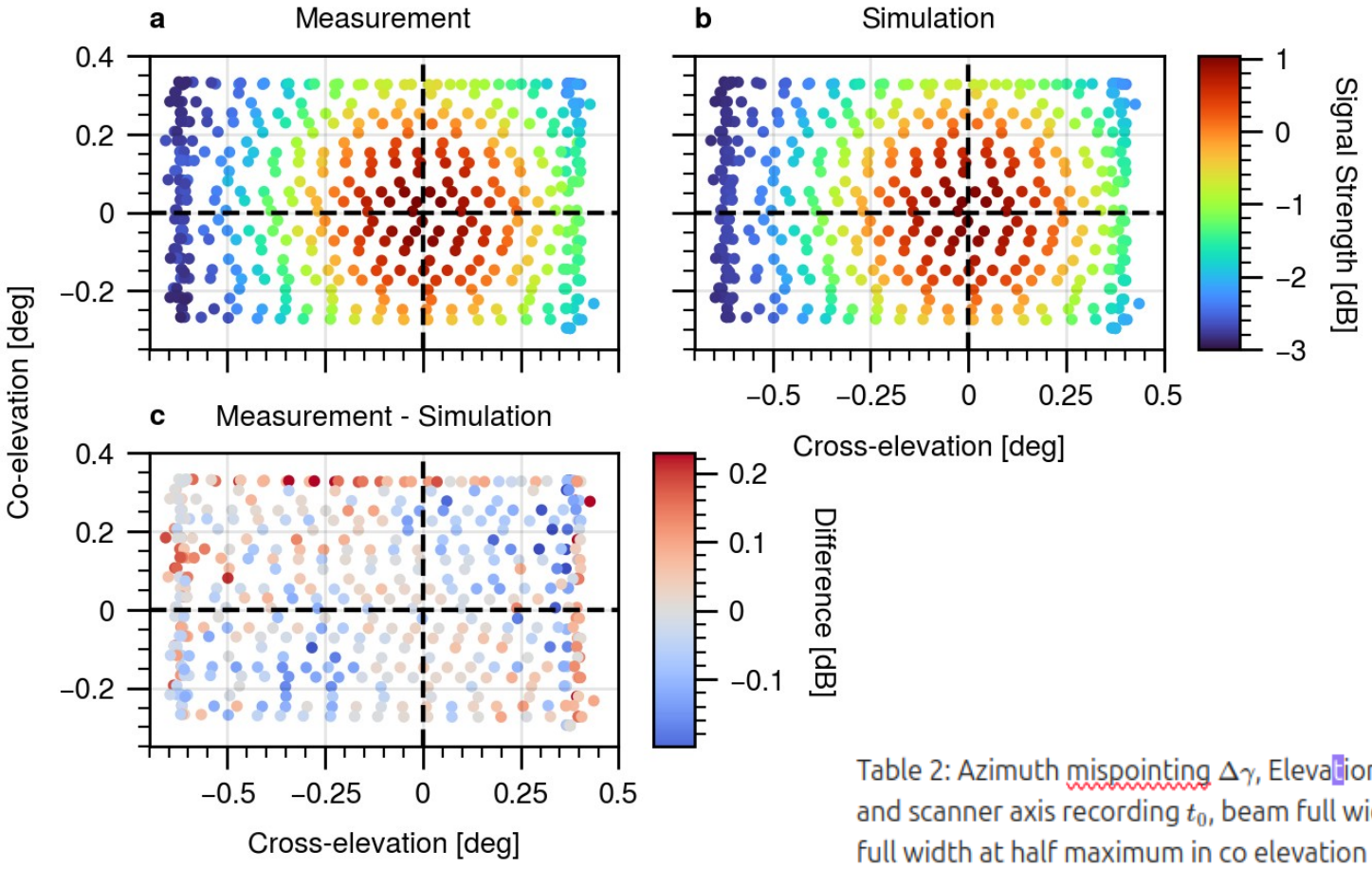
Sun Scan Simulated



Beam centered coordinates



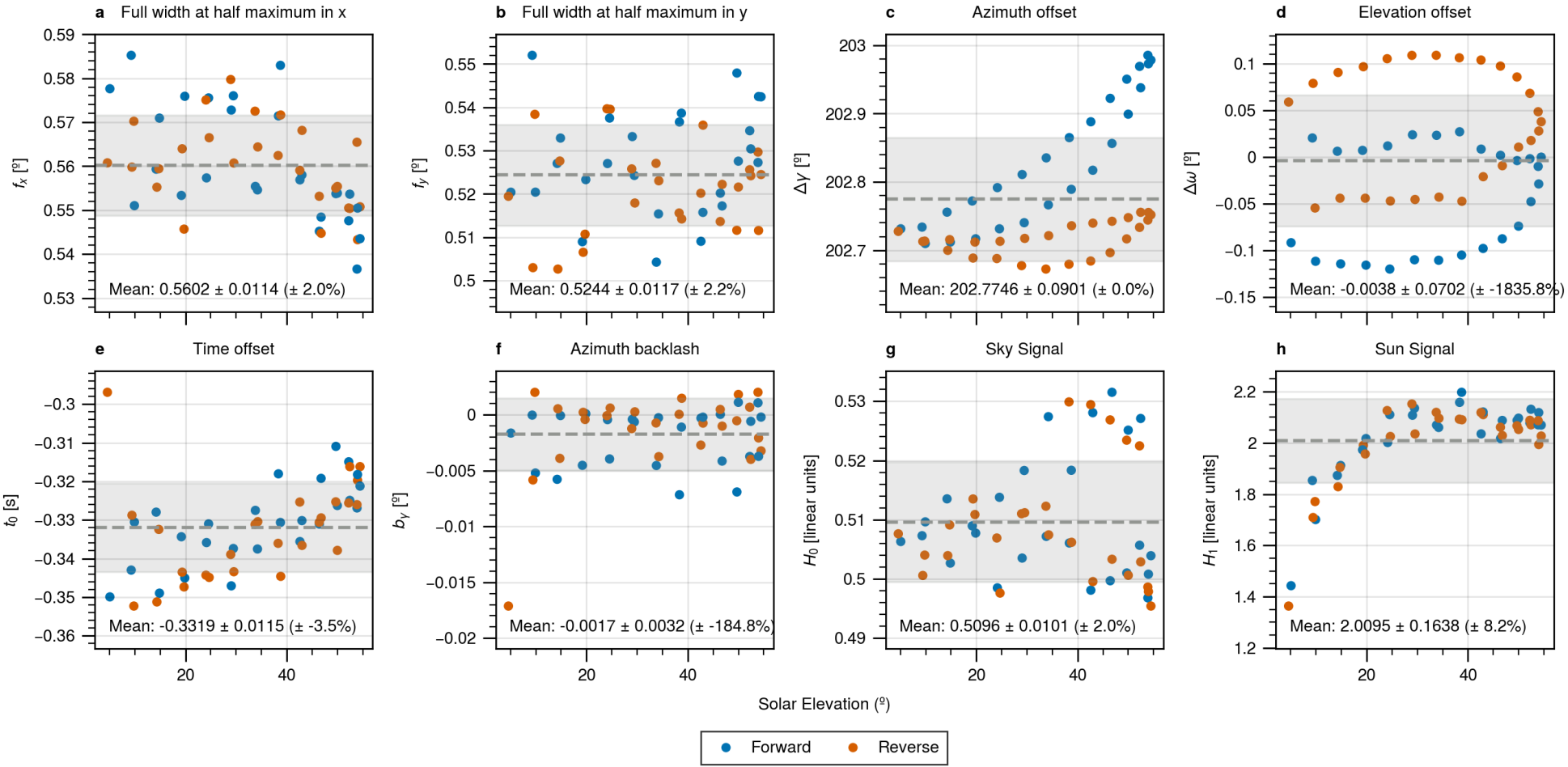
Sun Scan Beam-Centered



Parameter	Value
$\Delta\gamma$ [°]	202.9730
$\Delta\omega$ [°]	-0.0287
t_0 [s]	-0.3182
f_x [°]	0.5505
f_y [°]	0.5425
b_γ [°]	-0.0037
H_0 [linear units]	0.5008
H_1 [linear units]	2.1184

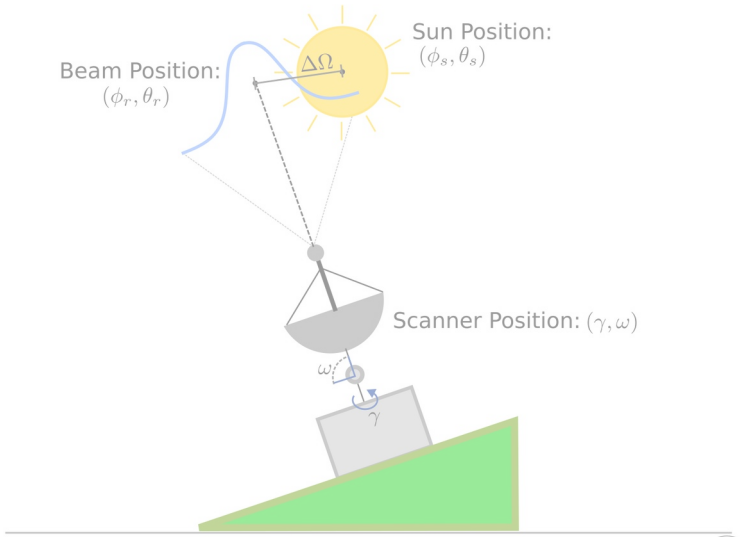
Table 2: Azimuth mispointing $\Delta\gamma$, Elevation mispointing $\Delta\omega$, time offset between signal and scanner axis recording t_0, beam full width at half maximum in cross elevation f_x, beam full width at half maximum in co elevation f_y, scanner backlash b_γ, sky brightness H_0, sun brightness H_1.

A Full Day of Sun Scans



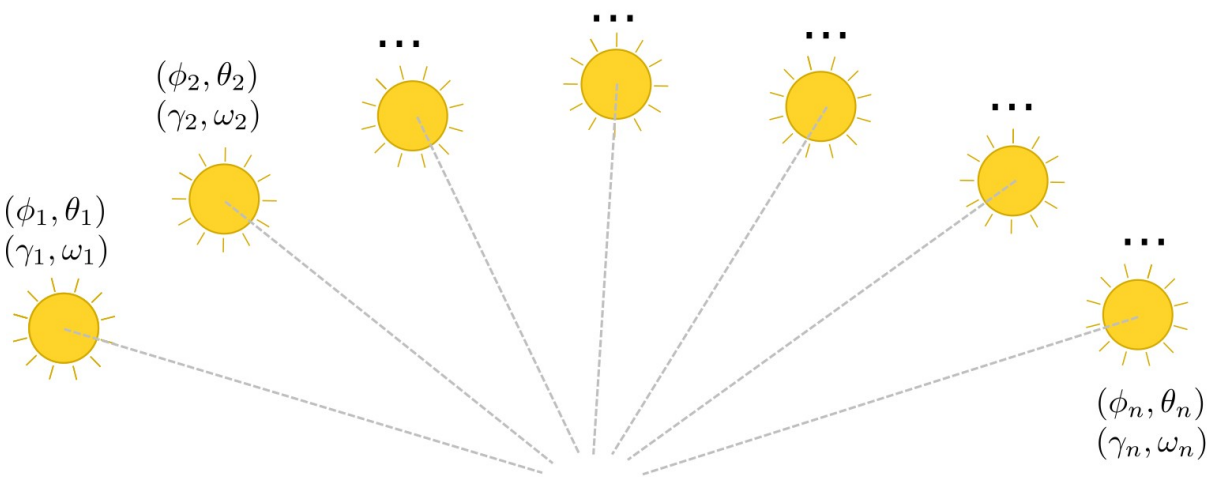
Step 2: Scanner Inaccuracies

Estimate local mispointing based on a single sunscan (1)



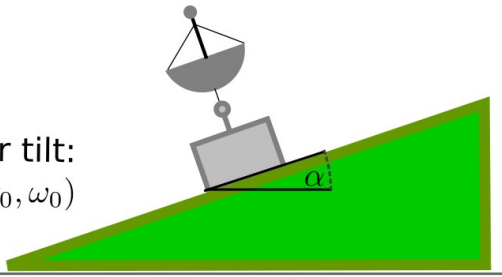
(2)

Estimate scanner tilts based on mispointing from many sunscans

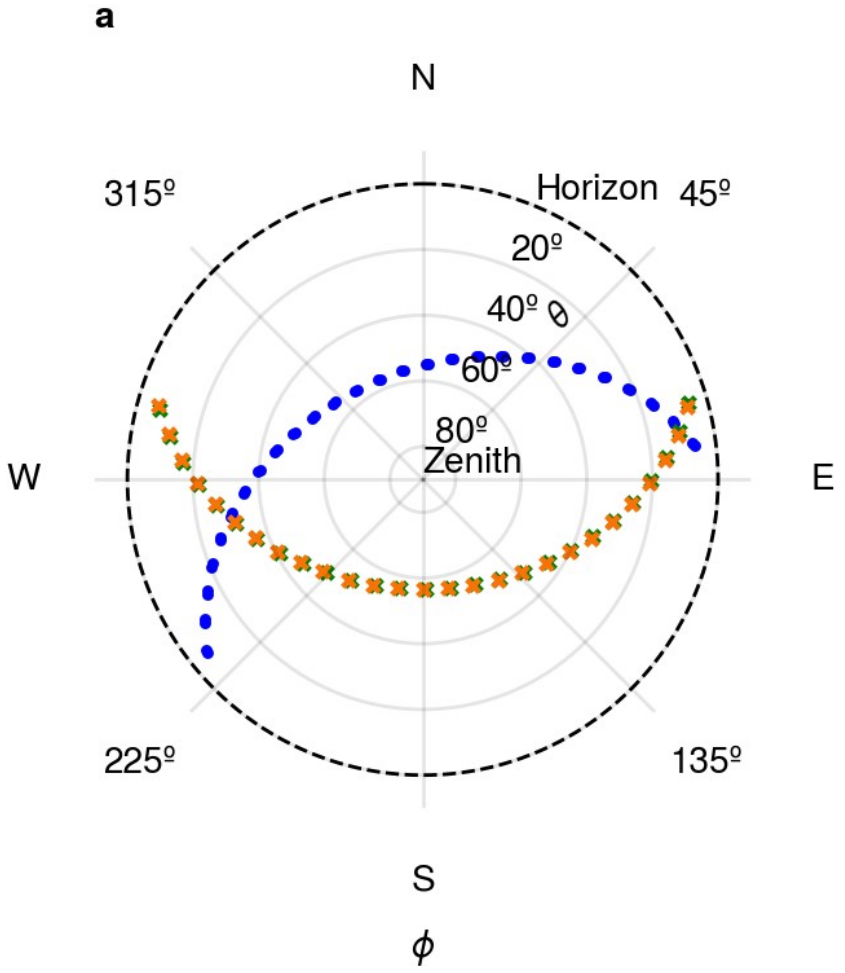


Estimate scanner tilt:

$\mathcal{F} = (\alpha, \beta, \delta, \epsilon, \gamma_0, \omega_0)$

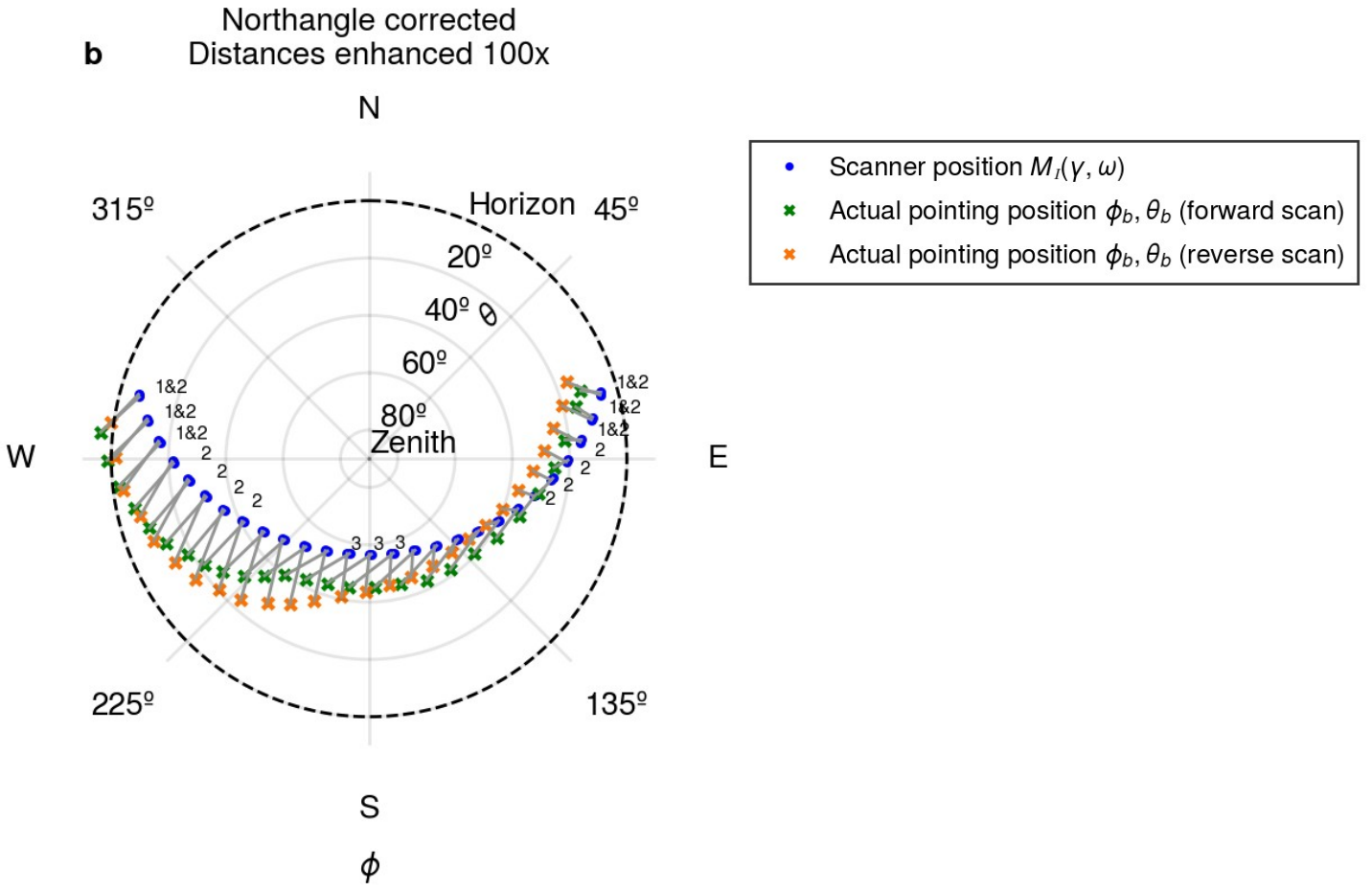


Uncorrected Mispointing



- Scanner position $M_i(\gamma, \omega)$
- Actual pointing position ϕ_b, θ_b (forward scan)
- Actual pointing position ϕ_b, θ_b (reverse scan)

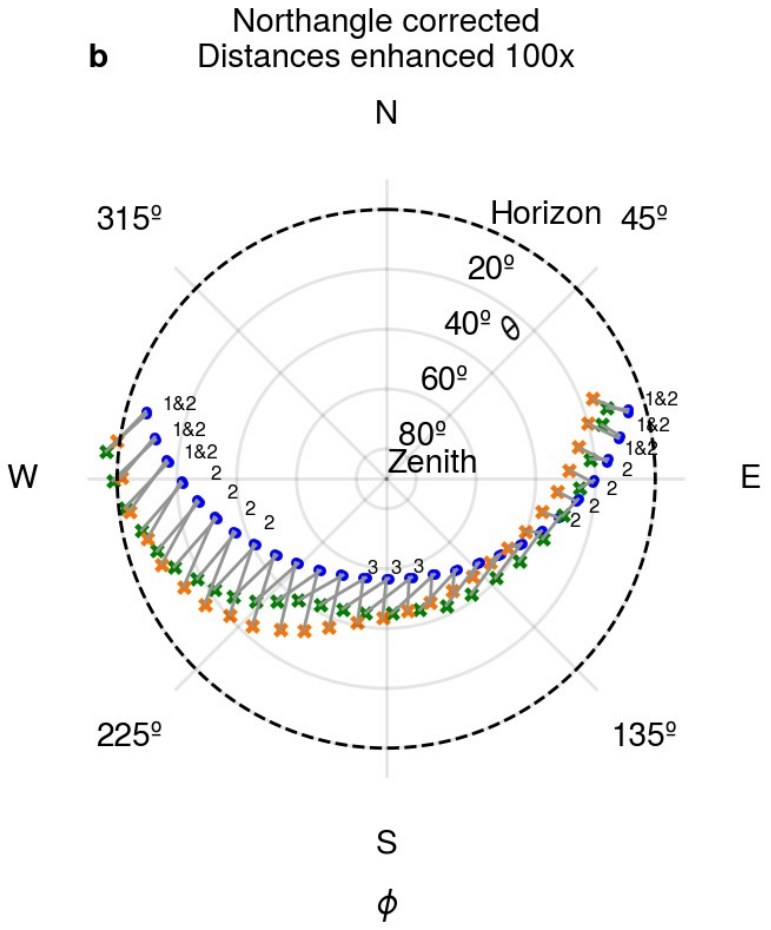
→ Turn by Northangle, Exaggerate Differences



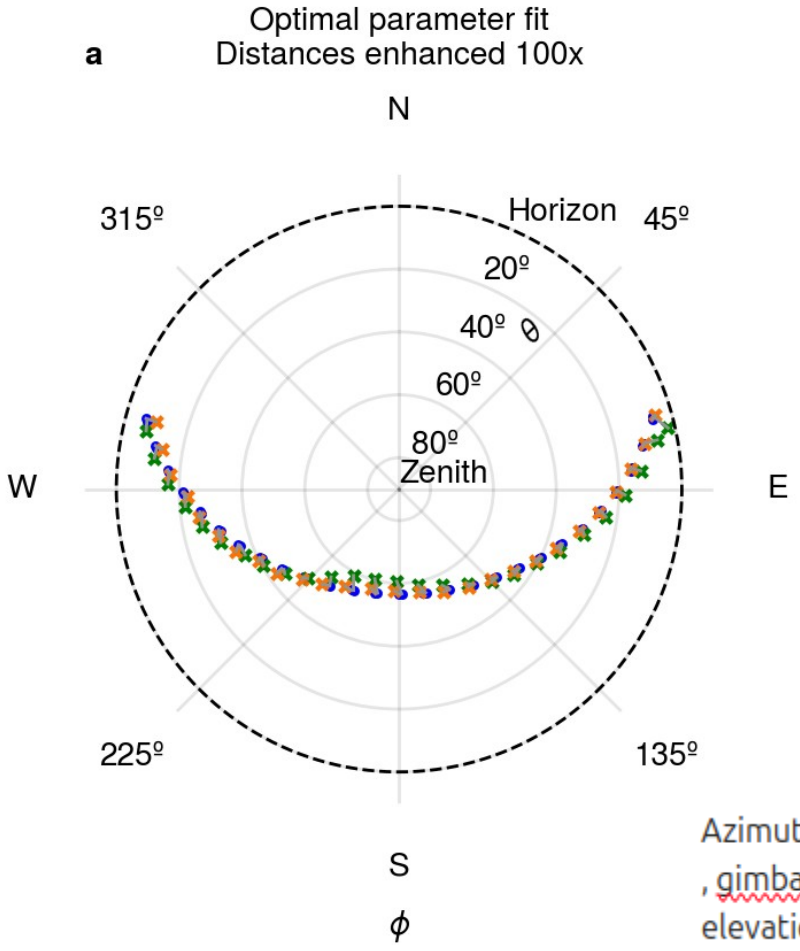
Fitting of 7 Unknown Parameters

Use sequential fitting:

1) Azimuth offset and antenna tilt: Use near horizon in West/East
2) West-East pedestal tilt and elevation offset: Use in West/East
3) North-South pedestal tilt and gimbal tilt: use high elevation in South
4) Re-optimize all parameters based on previously found initial guess



The Optimal Solution

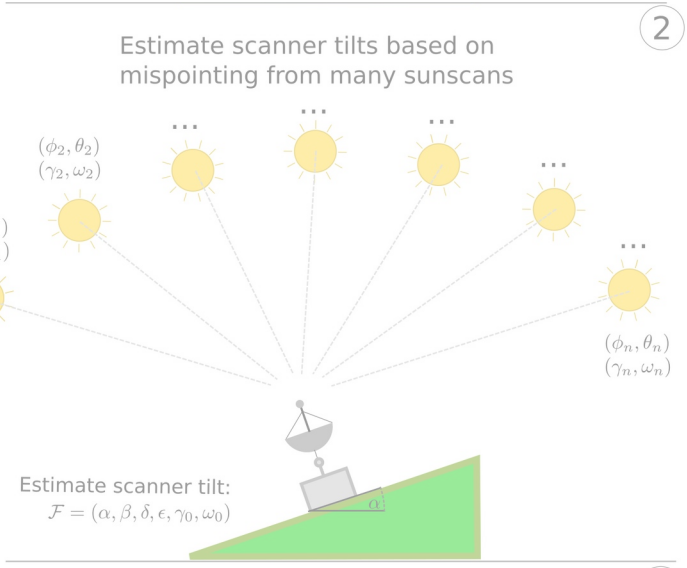


- Scanner position $M_1(\gamma, \omega)$
- Actual pointing position ϕ_b, θ_b (forward scan)
- Actual pointing position ϕ_b, θ_b (reverse scan)

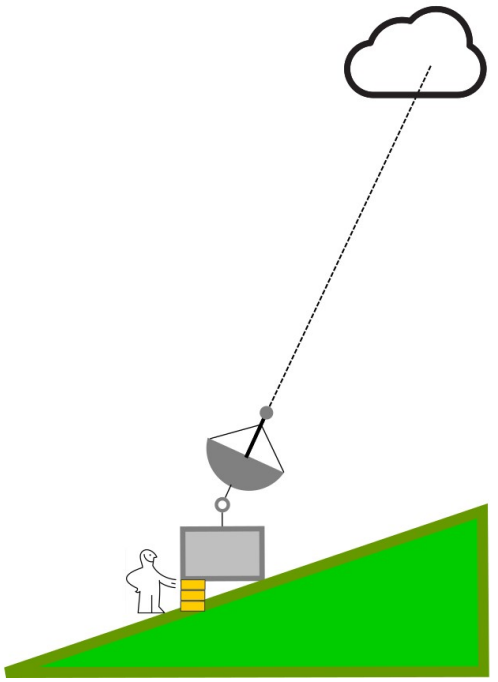
Parameters	Optimal Fit $\mathcal{F}_1$
γ_0 [°]	202.7284
ω_0 [°]	-0.0032
α [°]	0.1129
δ [°]	-0.1254
β [°]	-0.0887
ϵ [°]	0.0089
t_0 [s]	-0.3305
b_γ [°]	-0.0021
χ [°]	-0.0370

Azimuth offset γ_0, elevation offset ω_0, West-East pedestal tilt α, North-South pedestal tilt δ, gimbal tilt β, antenna tilt ϵ, signal-scanner time offset t_0, scanner backlash b_γ, elastic elevation deformation χ.

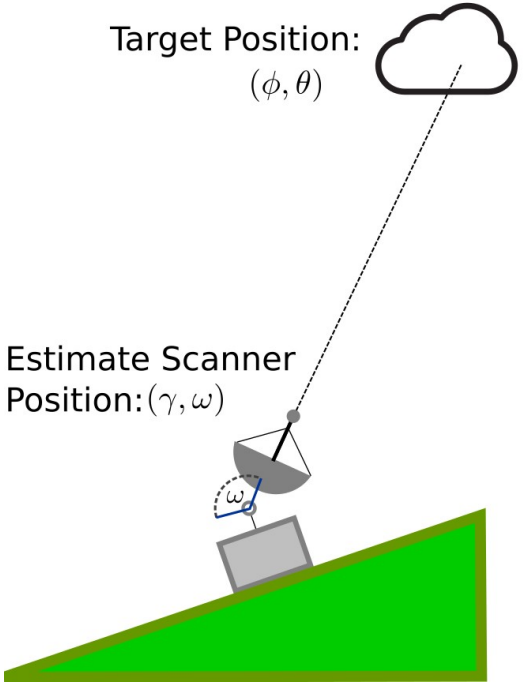
Step 3: Correction



a) Mechanically

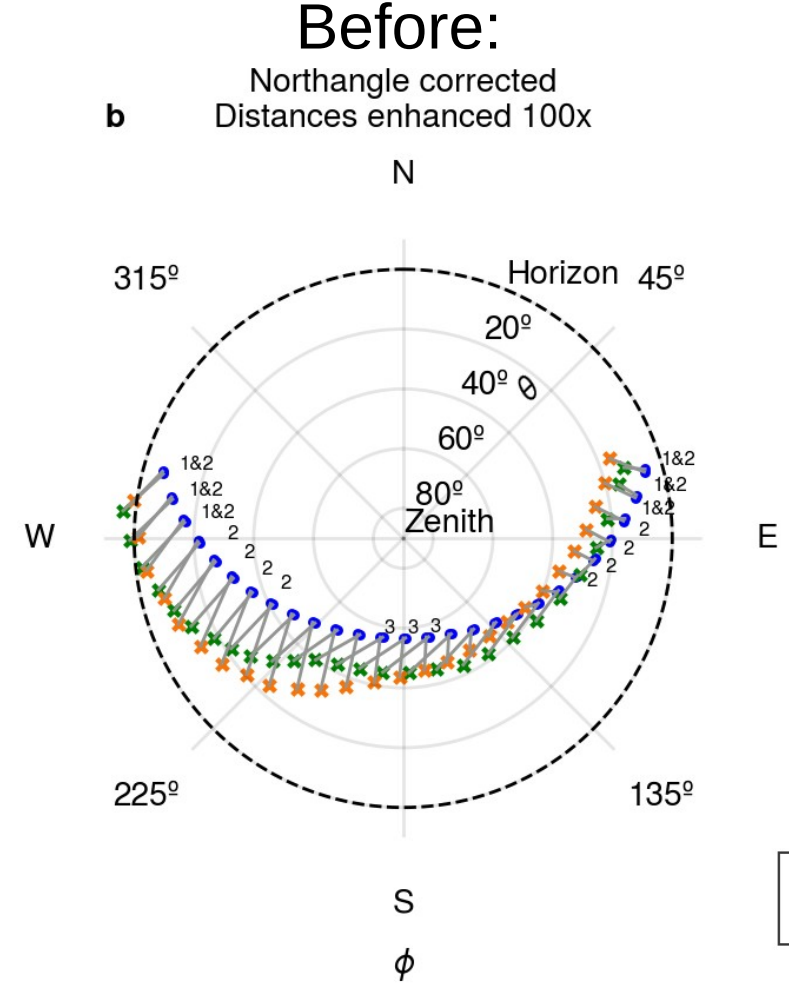


b) by Software

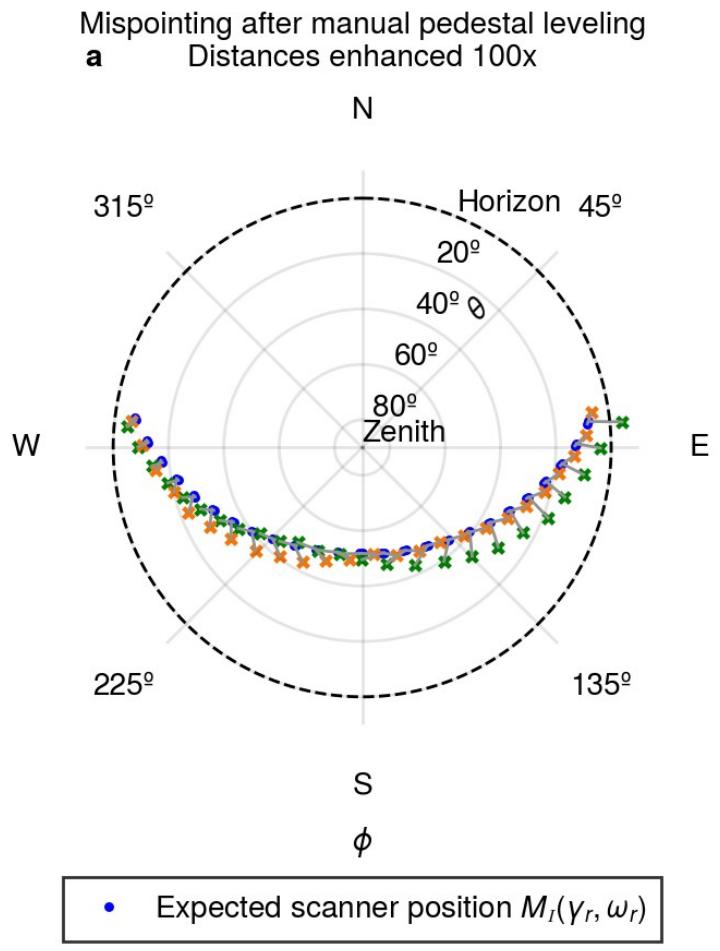


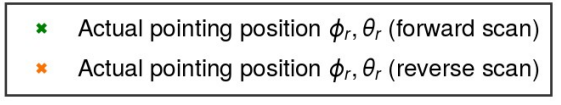
Mechanical Correction

Before:

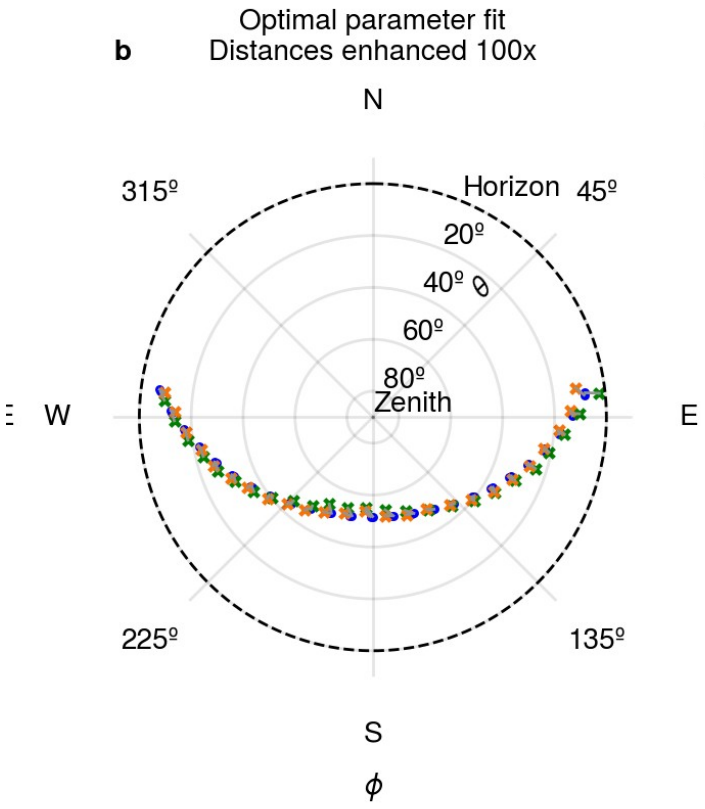


After:





The Optimal Solution After Manual Correction



Parameters	Optimal Fit $\mathcal{F}_1$	Optimal Fit $\mathcal{F}_2$ after manual leveling
γ_0 [°]	202.7284	202.7490
ω_0 [°]	-0.0032	-0.0081
α [°]	0.1129	-0.0105
δ [°]	-0.1254	0.0011
β [°]	-0.0887	-0.0873
ϵ [°]	0.0089	0.0078
t_0 [s]	-0.3305	-0.3304
b_γ [°]	-0.0021	-0.0029
χ [°]	-0.0370	-0.0491

Azimuth offset γ_0, elevation offset ω_0, West-East pedestal tilt α, North-South pedestal tilt δ , gimbal tilt β, antenna tilt ϵ, signal-scanner time offset t_0, scanner backlash b_γ, elastic elevation deformation χ.

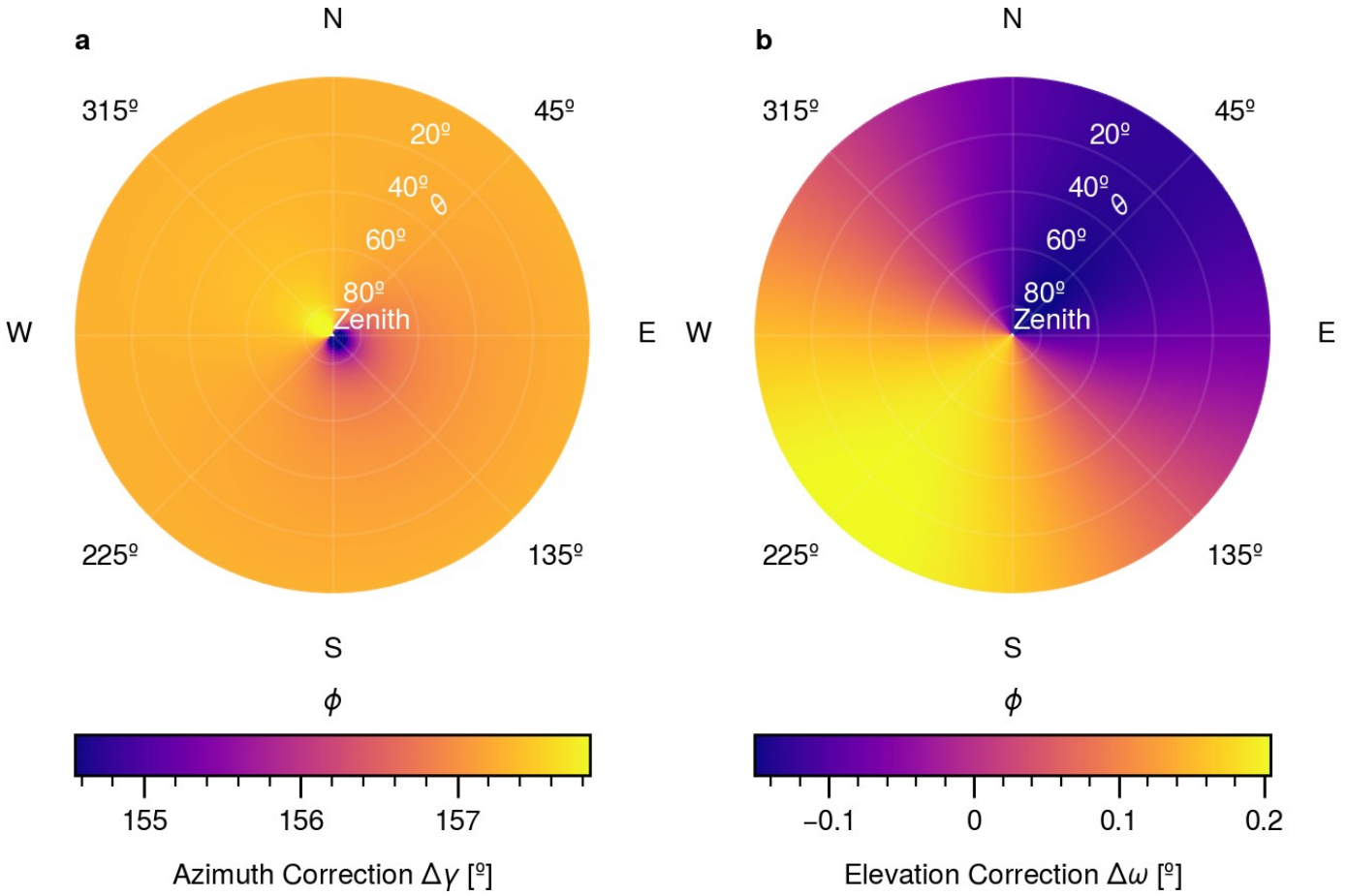
Automatic Correction by Inverse Kinematics

$$\mathrm{M}_{\mathcal{F}}^{-1}(\phi = 0°, \theta = 30°) = \begin{cases} \gamma = 157.30°, & \omega = 29.91°, \\ \gamma = 337.38°, & \omega = 150.10°. \end{cases}$$

Zenith Example

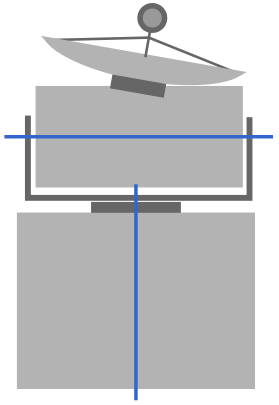
$$\mathrm{M}_{\mathcal{F}}^{-1}(\phi = 0°, \theta = 90°) = \begin{cases} \gamma = 171.06°, & \omega = 89.85°, \\ \gamma = 47.47°, & \omega = 90.15°. \end{cases}$$

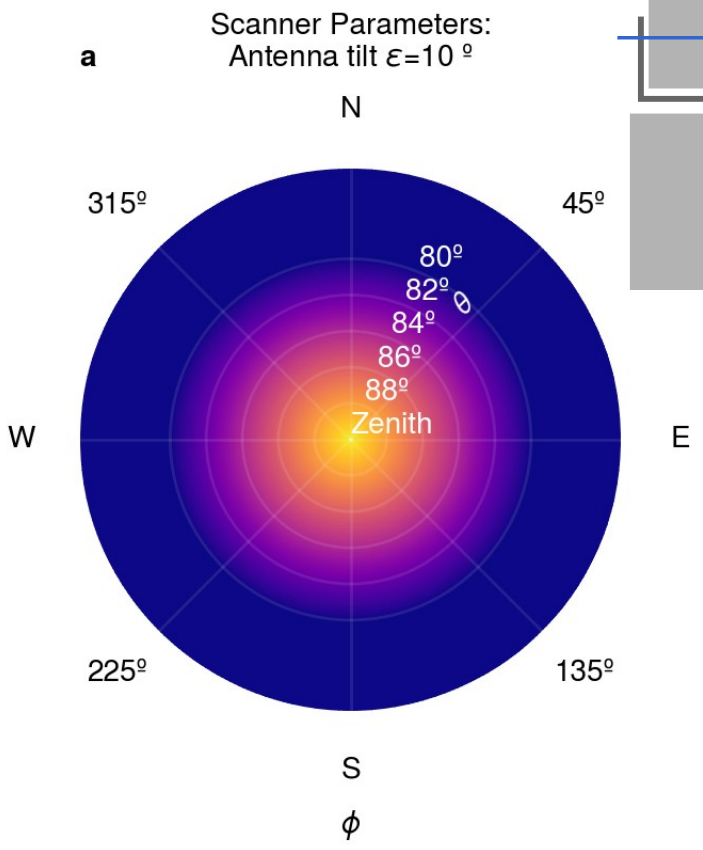
Automatic Correction by Inverse Kinematics



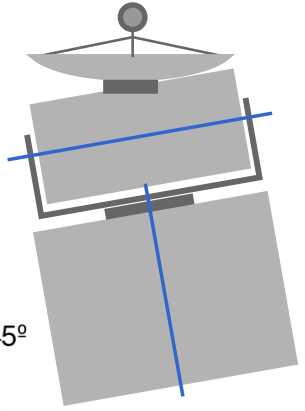
Should You Level Your Pedestal?

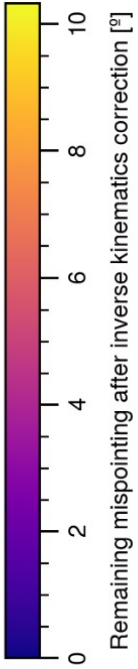
Perfectly level scanner





Tilted scanner



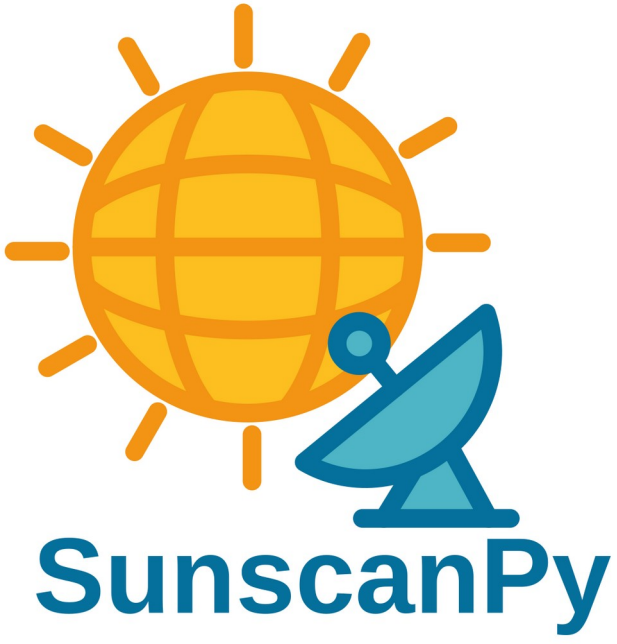


Wrap Up

- From Sun scans, we can derive beamwidth, time offset, gear backlash as well as all kind of static and dynamic scanner tilts and offsets
- With this knowledge, we can either correct inaccuracies physically or apply inverse kinematics for automatic correction

  → Do Sun scans! Even if you don’t correct the pointing immediately, if you have sunscan data available, you have the potential to estimate your pointing offsets in existing datasets in hindsight

Next



https://github.com/Ockenfuss/sunscanpy

Backup: Refraction Correction