Modeling of propagation in the neutral atmosphere for radio astronomy data analysis: a paradigm shift

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Problem statement:

Propagation effects:

- Path delay
- Refraction, i.e. trajectory bending
- Attenuation
- Atmosphere emission

If we know 3D state of the atmosphere, we can compute these quantities.

The crux of the problem: **the state of the atmosphere cannot be deduced from surface measurements**.

Reason: mixing ratio of water vapor is highly volatile.

Past

Paradigm: we do not know a priori state of the atmosphere.

How to circumvent the problem?

- to take a greatly simplified or just wrong a priori model. Errors for path delay: 85–95% (i.e. 300–1300 ps in zenith).
- to use the radio astronomy data themselves to solve to residual atmosphere related parameters.

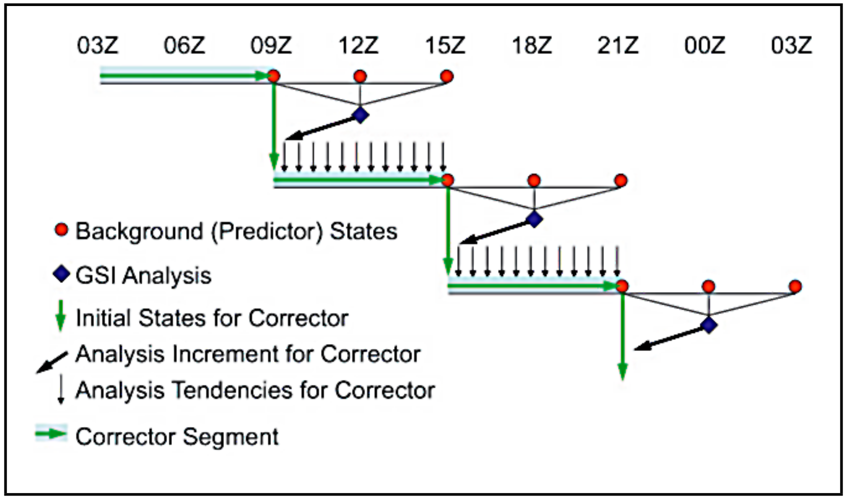
  Examples:

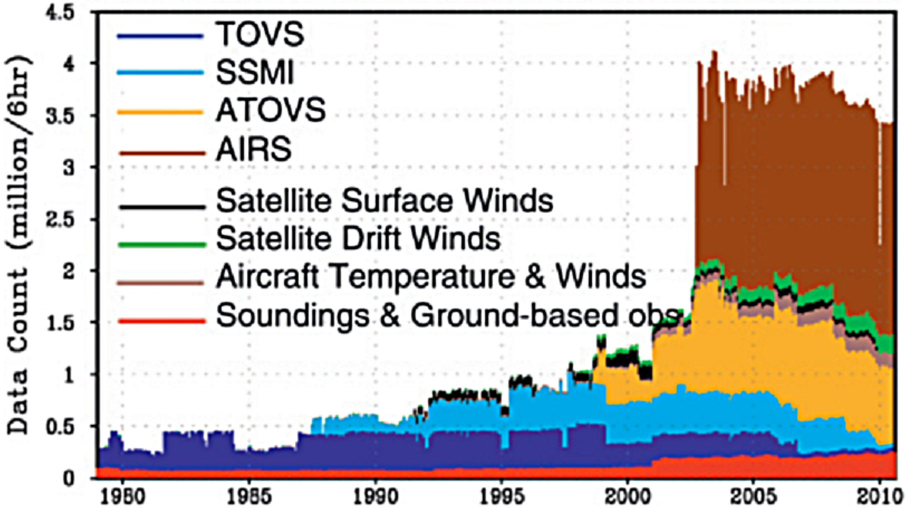
  - “geodetic blocks” in astrometry projects;
  - tipping curves for amplitude calibration.

Present

Numerical weather models (NWM) reached that level of sophistication that one can deduce the 4D state of the atmosphere.

How does an NWM work:





- we solve differential equat. and predict state of the atmosphere for ΔT;
- we ingest observations;
- we reconcile them during incremental analysis update (IAU) phase.

Observations are assimilated to the model using the 3D-Var scheme.

The output of models are huge 4D arrays of atmospheric variables (~ 300 Tb).

Once can restore 4D state of the atmosphere from these variables: P, P_w, T

There are four centers producing NWM: NASA GSFC, NOAO, ECMWF, JMA.

Model used:

MERRA:	Since 1979.01.01	72 lev $\times 0.5^\circ \times 0.67^\circ \times 6^h$	Latency: 40^d
GEOS FPIT	Since 2000.01.01	72 lev $\times 0.5^\circ \times 0.67^\circ \times 3^h$	Latency: 12^h

Data processing pipeline:

- Download the NWM output;
- Extract input variables;
- Compute P, P_w, T;
- Re-grid;
- Compute air refractivity and air specific attenuation;
- Expand them into 3D B-spline basis.

Computation of Atmospheric Propagation Parameters (APP): path delay, refraction angle, atmosphere opacity, and atmosphere brightness temperature.

Basis: Fermat principle (1662).

- Variational problem $\longrightarrow$ differential equations for the trajectory;
- Numerical solution of equations $\longrightarrow$ trajectory;
- Integration of specific attenuation and refractivity $\longrightarrow$ APP for each station;
- For each station expansion of the APP field over elevation, azimuth, and time;
- Ingestion of this expansion into a data analysis package.

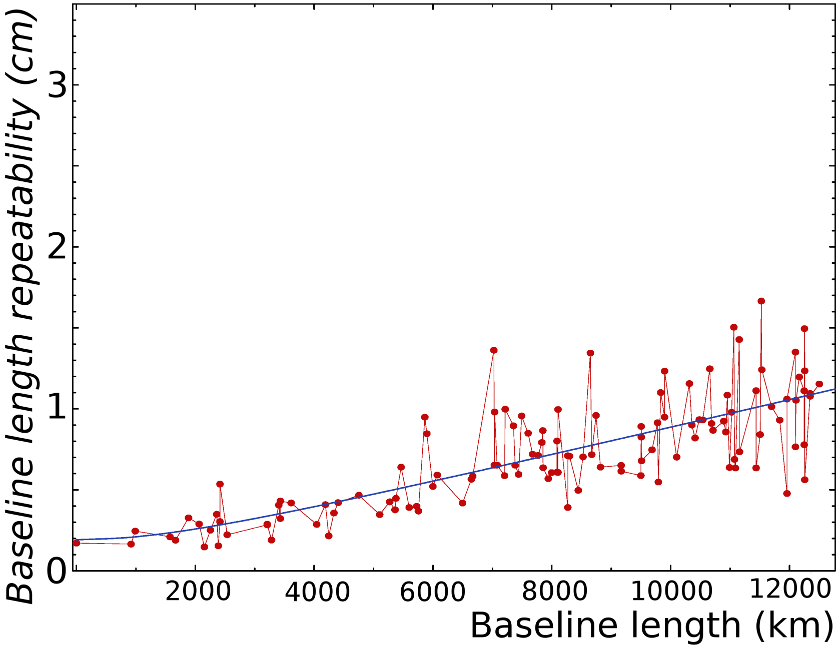
Dataset used: MERRA 1979.01.01 – 2014.09.26, GEOS FPIT 2000.01.01 – 2014.09.25, 220 VLBI stations. Input dataset: 17 Tb, output dataset: 0.17 Tb, processing time: 15^d at a desktop computer.

Validation of results:

Path delay validation:

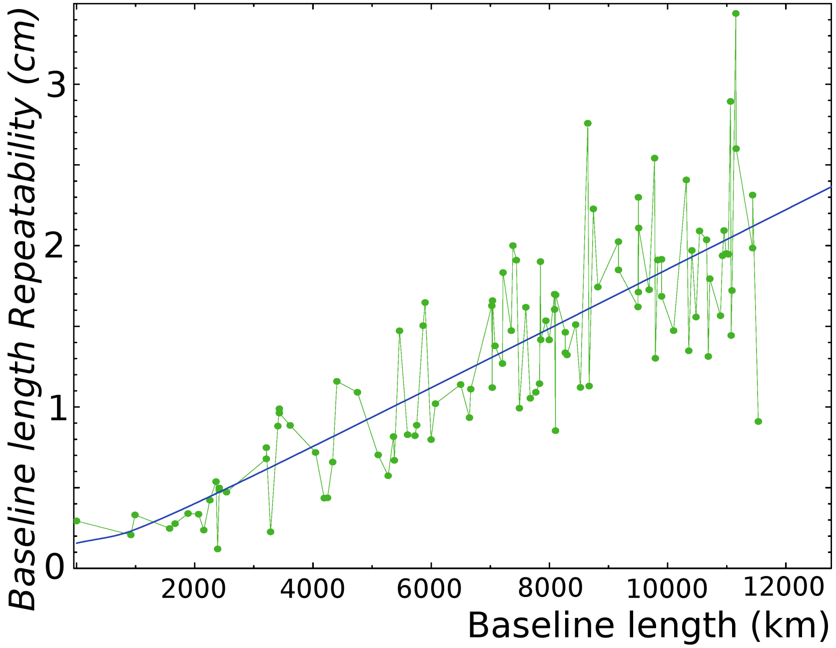
- Geodetic solution with APPs from GEOS-FPIT against a traditional solving with estimating atmosphere path delay in zenith direction
- Analysis of residual path delay estimates after applying APPs from GEOS-FPIT

Baseline length test



Traditional approach: zenith path delay is solved for.

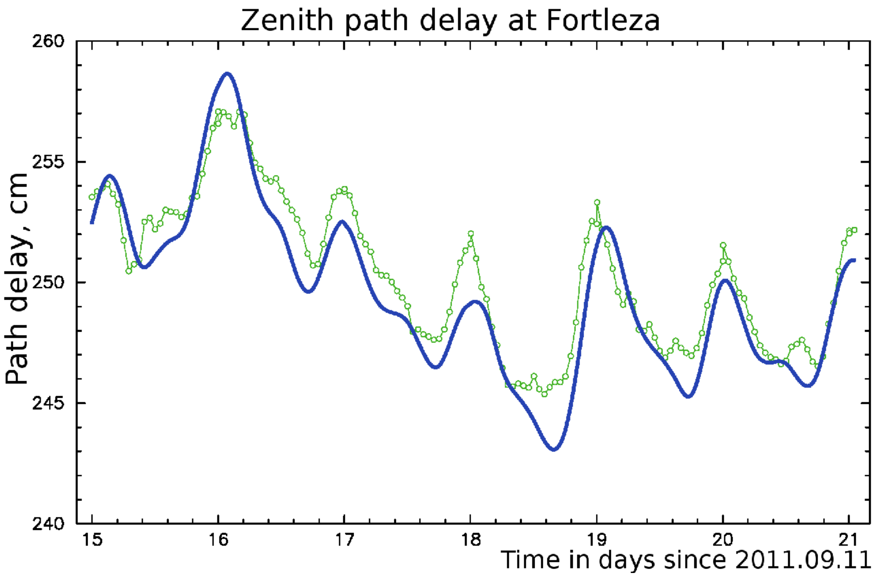
Baseline length repeatability at Earth diameter is 1.12 cm.

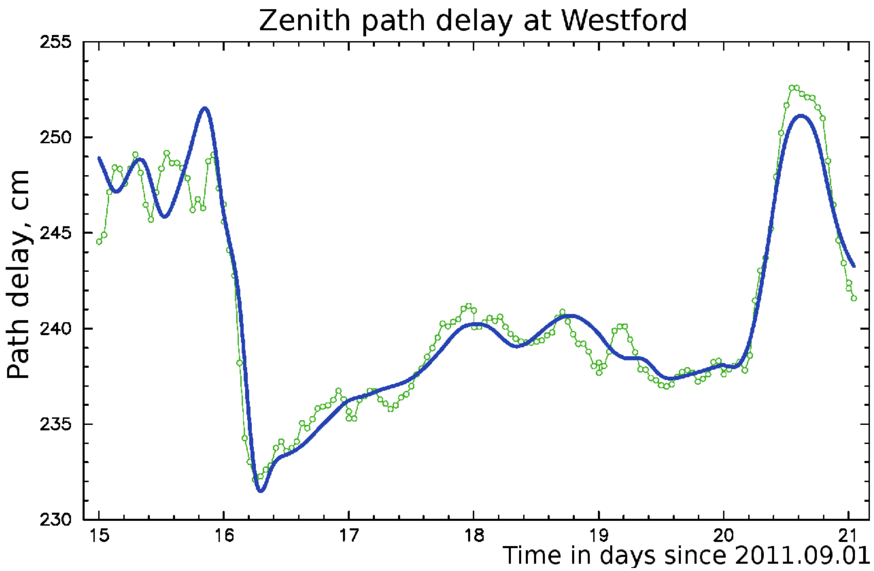


APP approach: slant path delay computed from GEOS-FPIT.

Baseline length repeatability at Earth diameter is 2.32 cm.

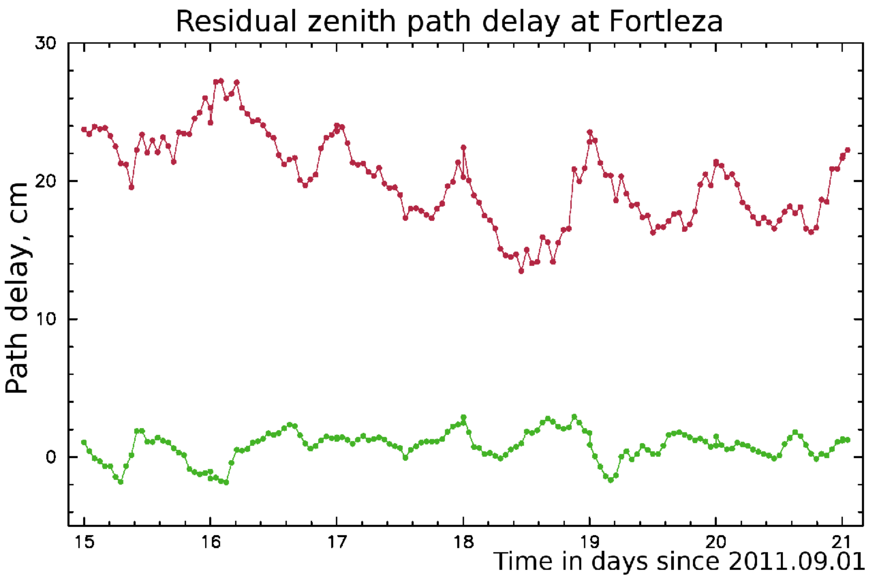
Additional variance: **1.45 cm** (43 ps)

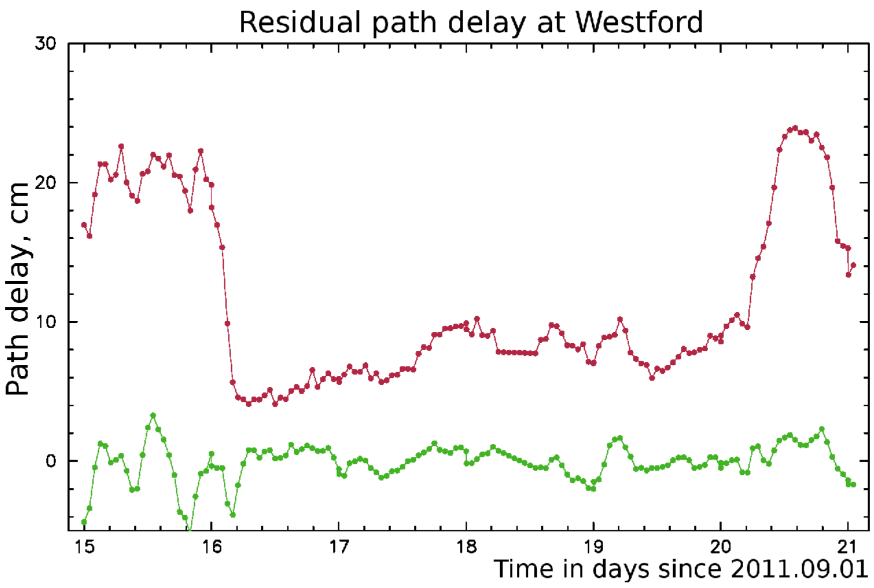




Blue line: A priori zenith path delay computed using GEOS-FPIT model.

Green line: total path delay after parameter adjustment using VLBI observations.


Residual zenith path delay at Fortleza


Residual path delay at Westford

Red line: Residual zenith path delay with respect to Saastamoinen (1972) model that accounts only for surface pressure. The rms of residuals: 20.4 and 12.9 cm at Fortleza (Brazil) and Westford (USA, MA).

Green line: Residual zenith path delay with respect to a priori delay computed using GEOS-FPIT numerical weather model. The rms of residuals: 1.0 and 1.3 cm. In both cases the same set of VLBI

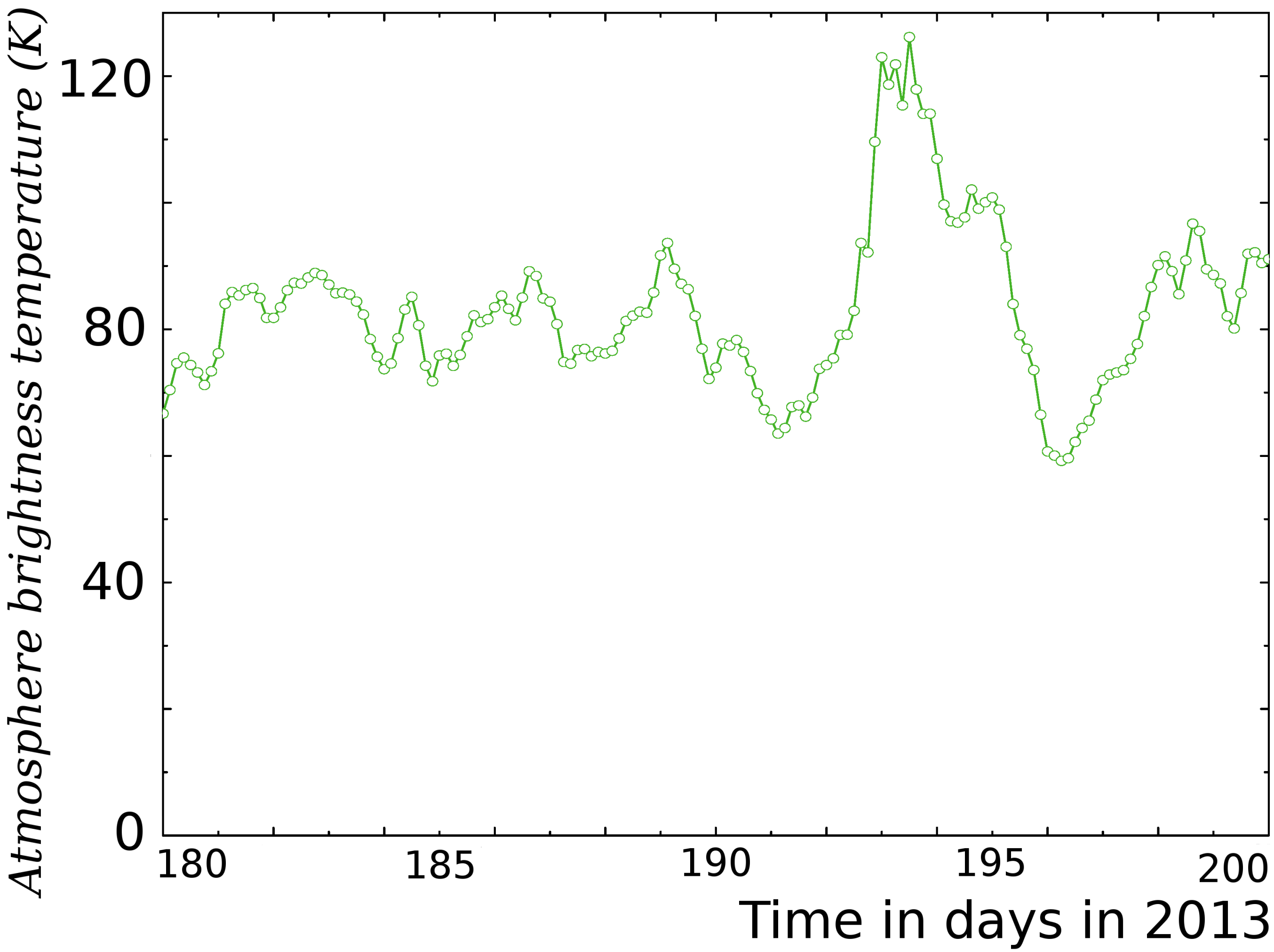
Statistics of residual zenith path delay from a global VLBI solution using all the data since 1980.04.08 through 2014.08.04:

station	# ses	wrms (cm)
NYALES20	1446	0.62
SYOWA	63	0.62
GILCREEK	1922	0.78
OHIGGINS	119	0.85
. . .		
MIAMI20	20	1.88
KWAJAL26	20	1.94
KATH12M	182	2.15
SC-VLBA	274	2.23
average		**1.35**

For comparison: total average zenith path delay: **251.36** cm.

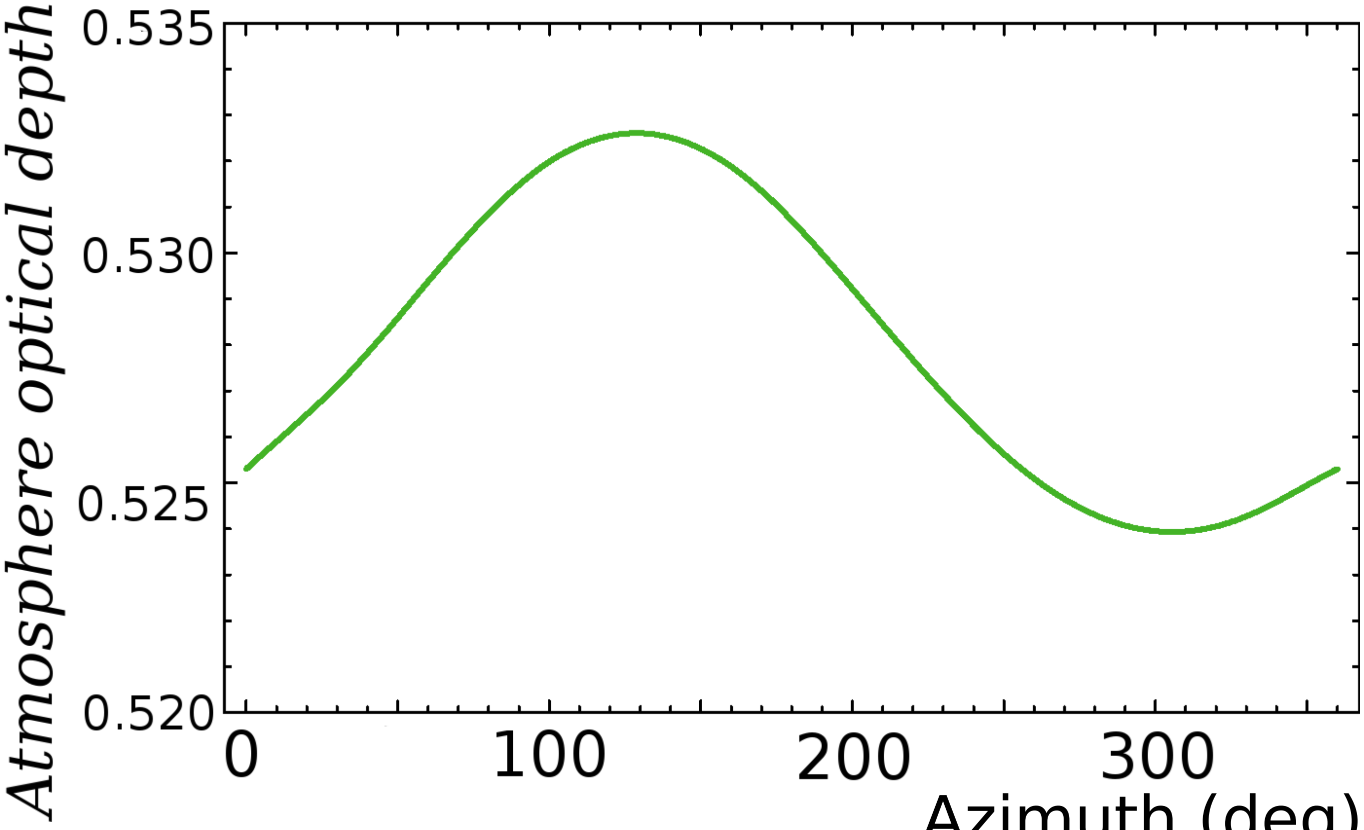
Atmosphere brightness temperature

Atmosphere brightness temperature in zenith direction in VERAISGK at 22.508 GHz



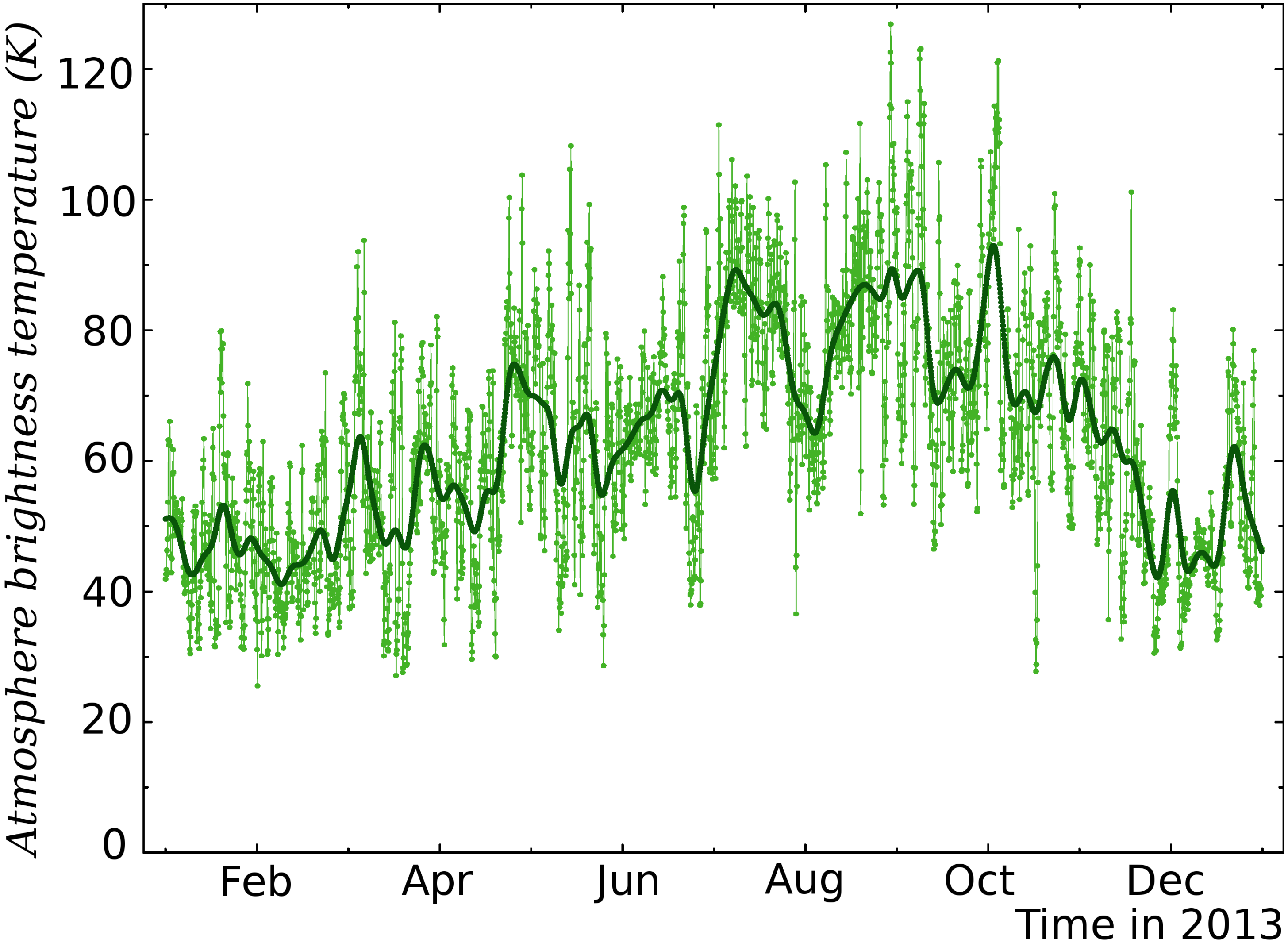
Atmosphere opacity

Atmosphere opacity at GBT on 2013.08.08_06:00 at elevation 20°.

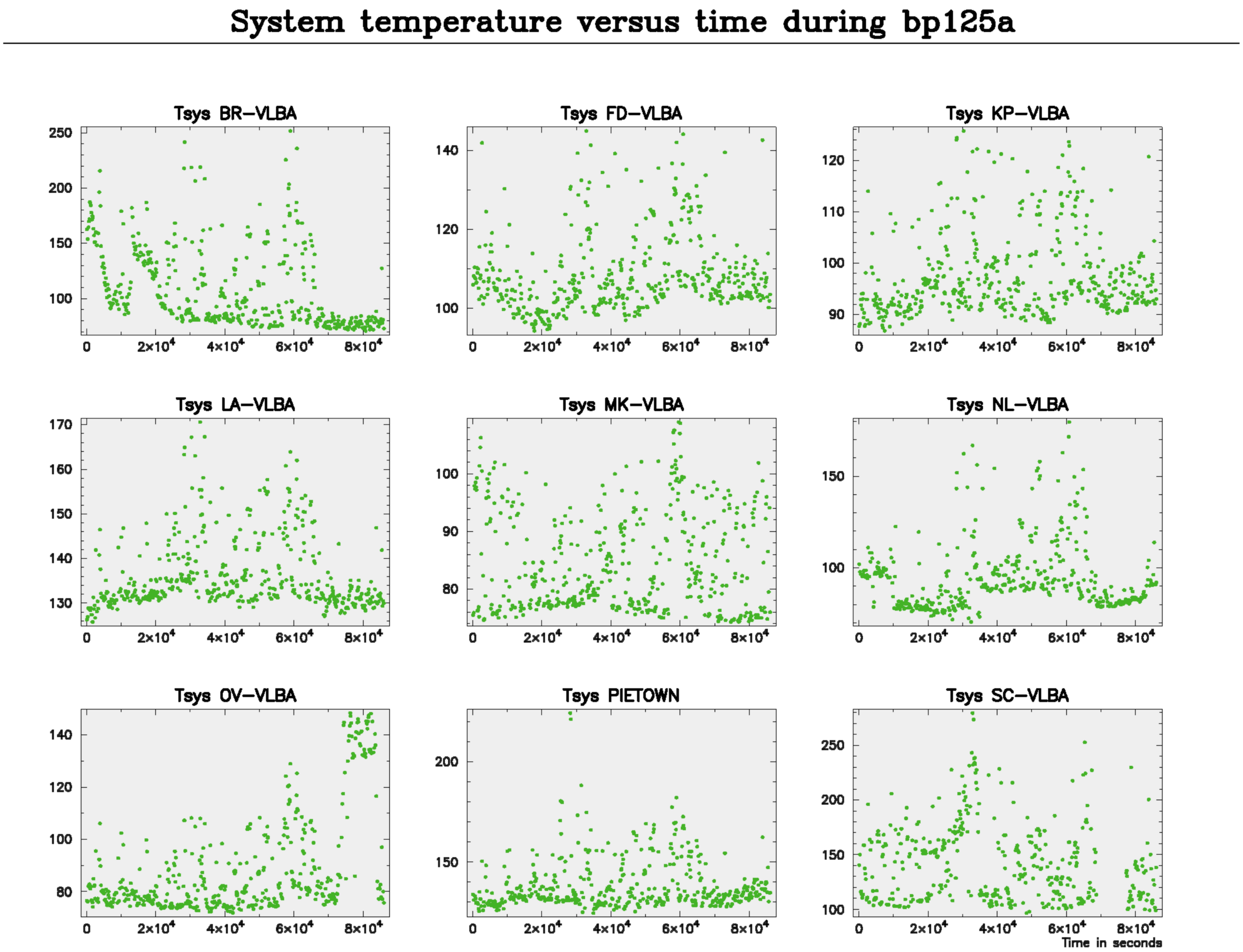


Atmosphere brightness temperature

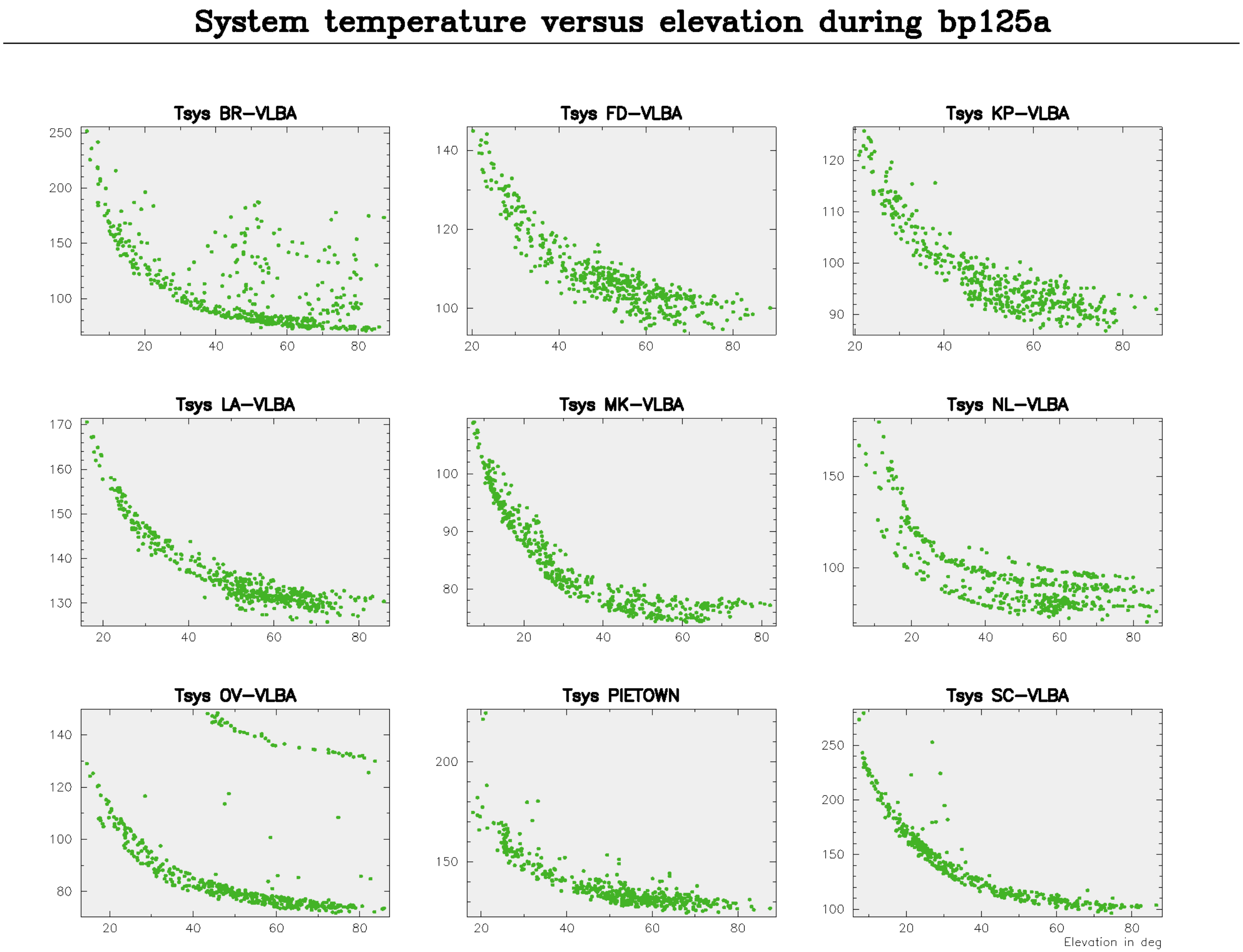
Atmosphere brightness temperature at elev 45° at SARDINIA at 86.304 GHz



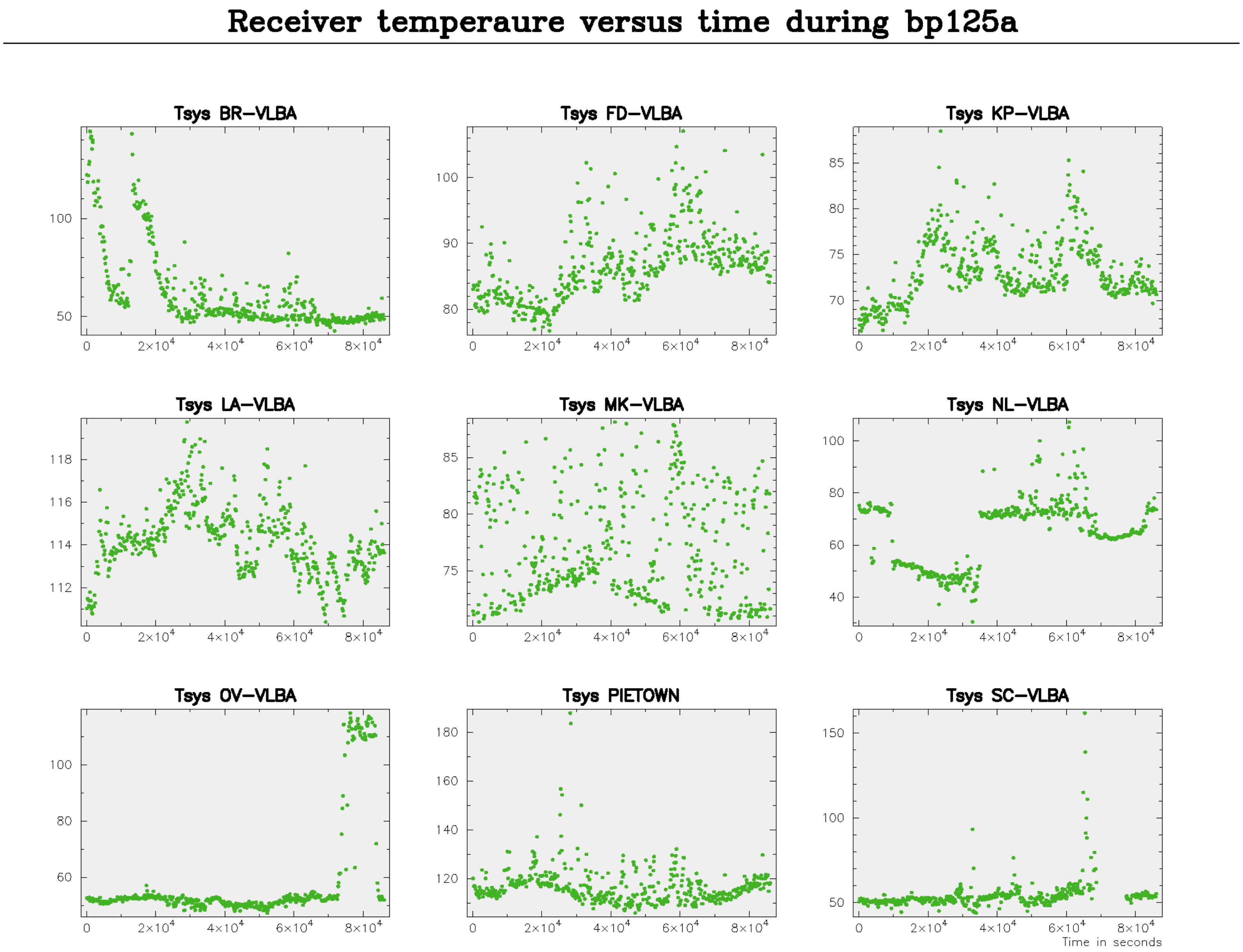
K-band system temperature



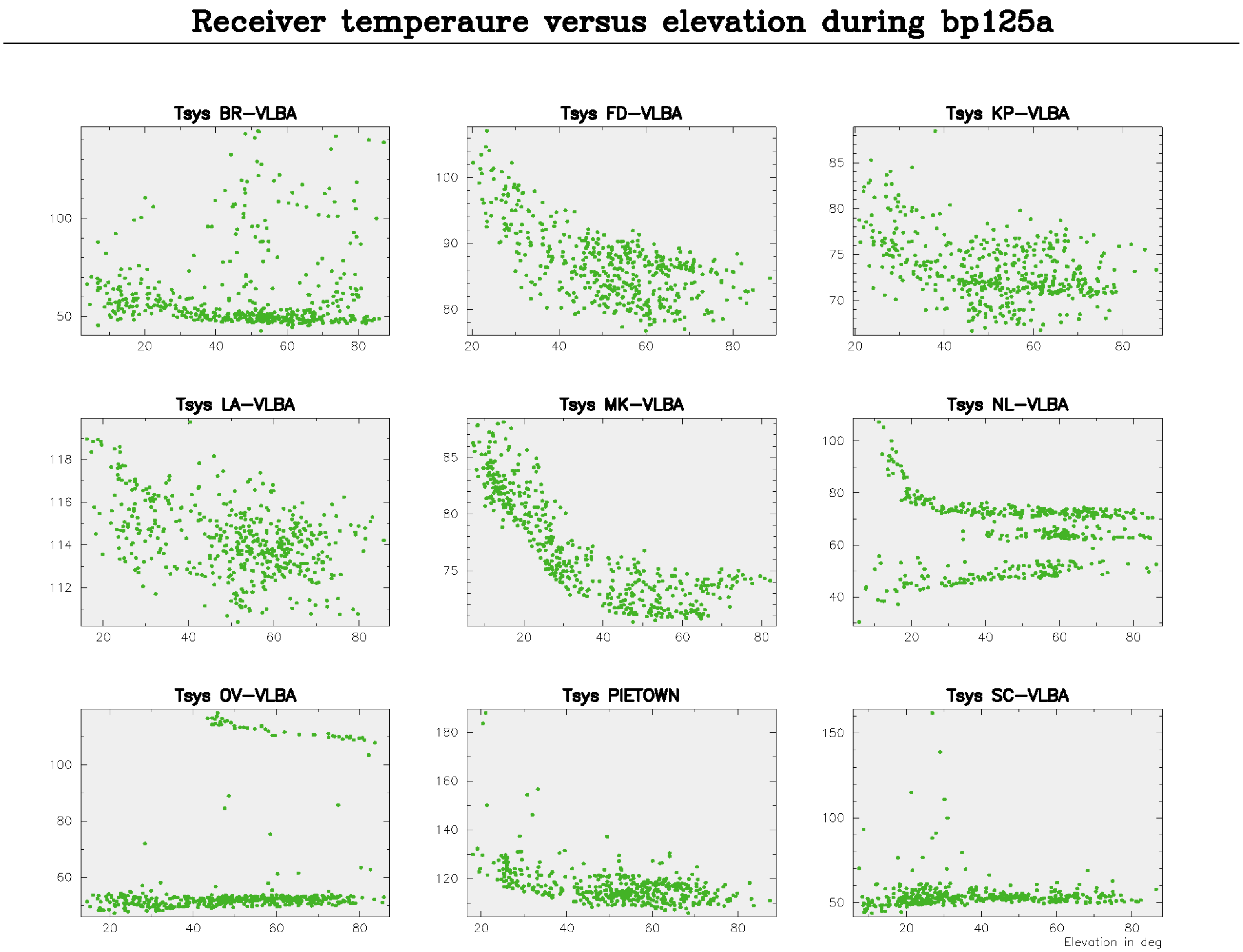
K-band system temperature



K-band system temperature with atmosphere temperature removed



K-band system temperature with atmosphere temperature removed


Receiver temperaure versus elevation during bp125a

Paradigm shift

Past	Present
We do not know state of the atmosphere	We know state of the atmosphere at the 4D grid
We solve for path delay using "geodetic blocks"	We compute path delay from the state of the atmosphere
A priori path delay is modeled with accuracy 85–95%	A priori path delay is modeled with accuracy 0.5%
We solve for atmosphere opacity by observing tipping curves	We compute atmosphere opacity from the state of the atmosphere
Uncertainty in atmosphere opacity is the major error sources at $f > 15$ GHz	Uncertainty in atmosphere opacity (gaseous contribution) is modeled with accuracy 0.5%

Future:

- Correction for atmospheric propagation is applied as easily as correction for light aberration
- APPs are distributed as a community service from dedicated sever(s) and seamlessly ingested into data analysis software
- a 24-hour forecast of APPs is used for observation planning
- Geodetic blocks, tipping curves are history
- Contribution of liquid water and snow is modeled
- Accuracy of NWMs is further improved

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