Impact of Gravitational Deformation of VLBI Antennas on Reference Frame

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Acknowledgements

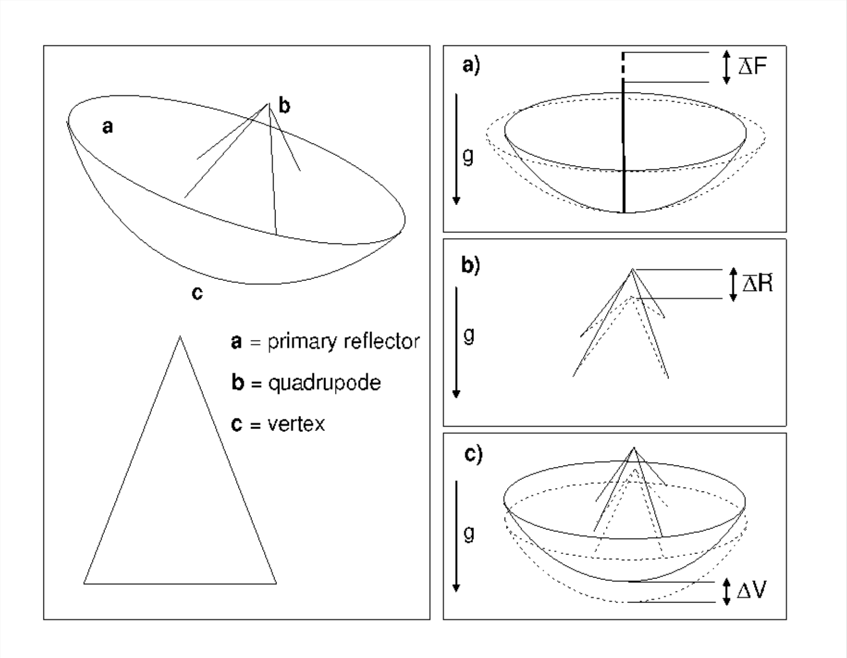
I am presenting the results of many other people’s work.

My major contribution is to collate and combine their results.

Agenda

- Overview of gravitational deformation
- Origin: Gilcreek case
- Antennas with models
- Effect on VLBI estimates
- Comparison with local ties
- Conclusions

Gravitational Deformation



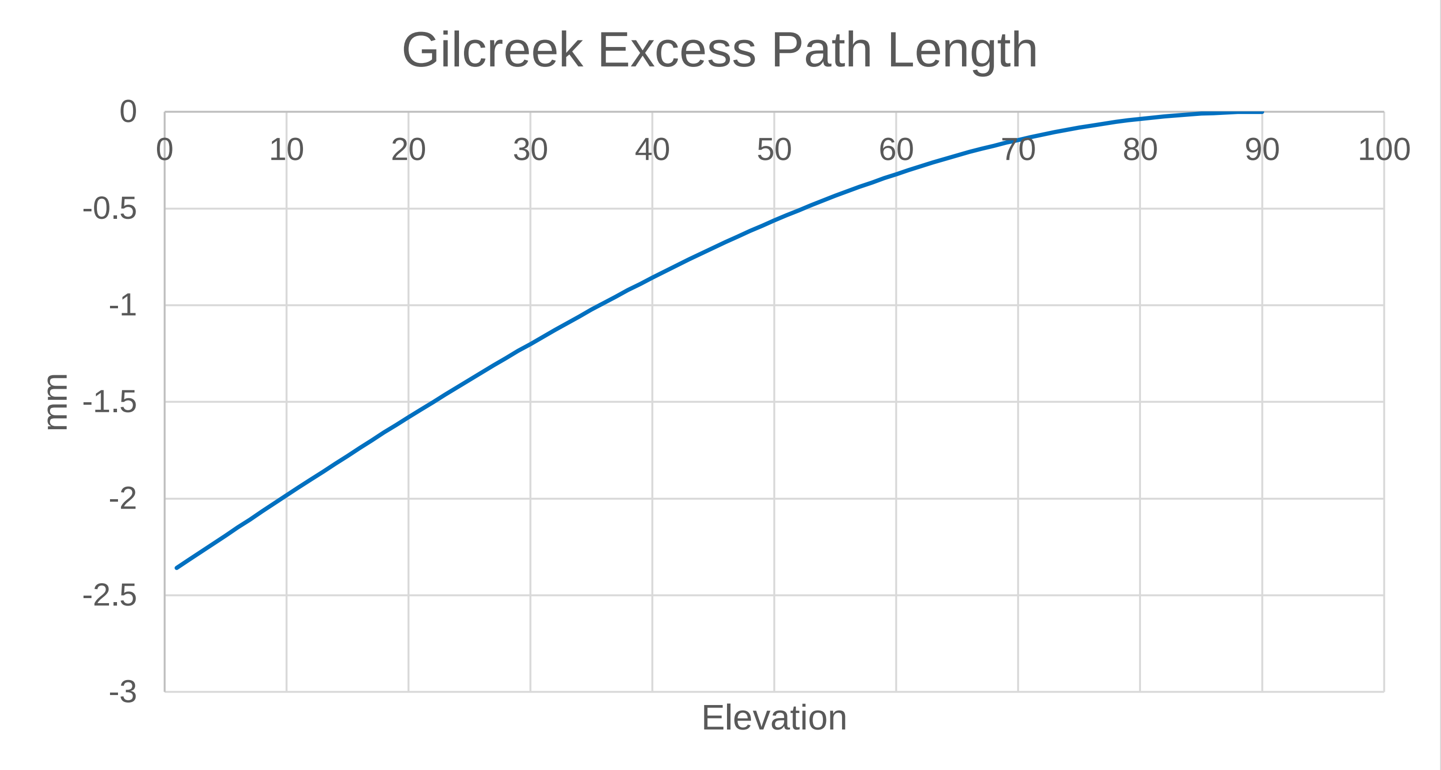
Clark and Thomsen (1988) model for signal path delay depends on variations of

1) focal length
2) vertex position
3) receiver position

$$\Delta L(e) = \alpha_F \Delta F(e) + \alpha_V \Delta V(e) + 2\alpha_R \Delta R(e)$$

- Coefficients depend on dimensions and structure of antenna
- The functions F, V and R have to be measured or modeled for each antenna

Effect at Gilcreek



$\Delta L(el) = 2.4(\sin(el) - 1)mm \longrightarrow$ Change in up estimate of 2.4 mm

At the time (1988—30 years ago!) this was considered a small effect, which is why no one paid much attention.

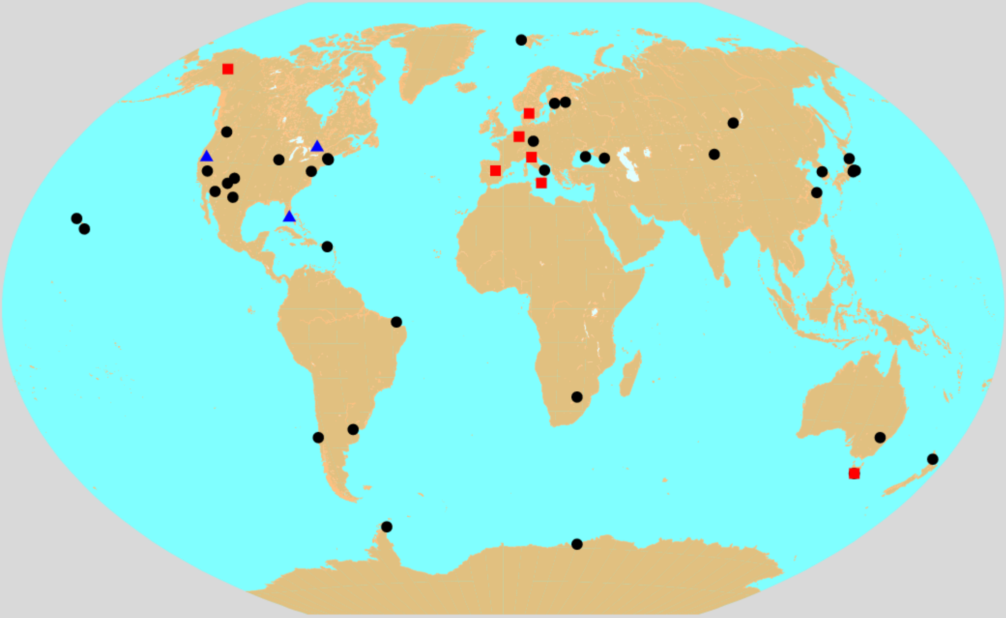
Antennas with models

When	Where	Who
1988	Gilcreek 26M	Clark & Thomsen
2005	Hobart 26M	Dawson et al *(Never published)*
2009	Medicina 32M Noto 32M	Sarti, Negusini, Abbondanza
2014	Yebes 40M	Nothnagel, et al
2014	Efflesberg 100M	Atz, Springer, Nothnagel
2018	Onsala60	Nothnagel et al

Each author gives a different functional form for $\Delta L(el)$

- This makes it difficult to incorporate in an antenna
- Difficult to understand the effect on estimated parameters

IVS Antennas with Models

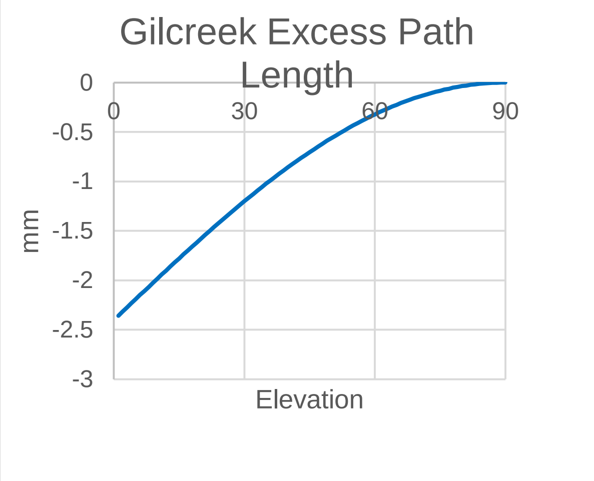


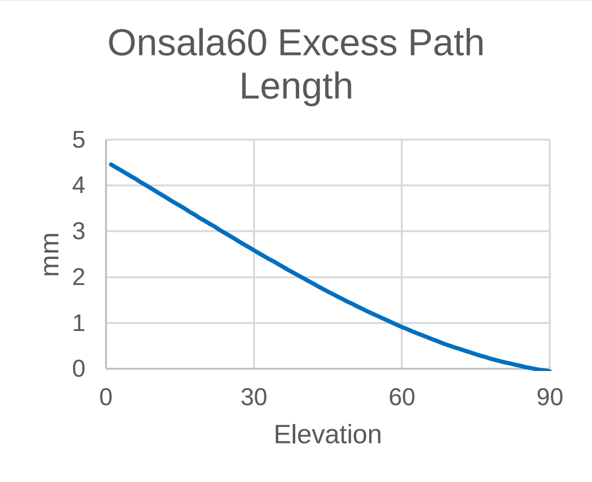
Only a small minority of VLBI antennas have models.

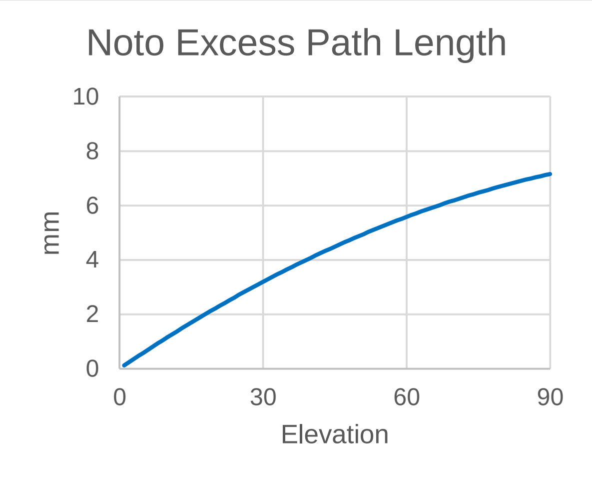
Some antennas were destroyed or decommissioned, and it is unlikely we will ever have models for these.

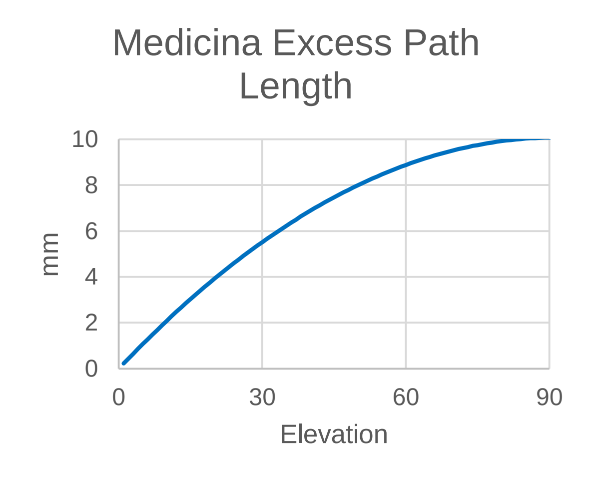
This figure only lists some of the defunct antennas for simplicity.

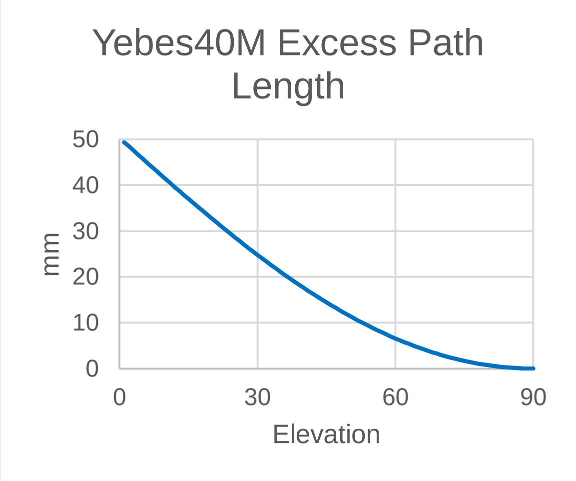
Summary of Models

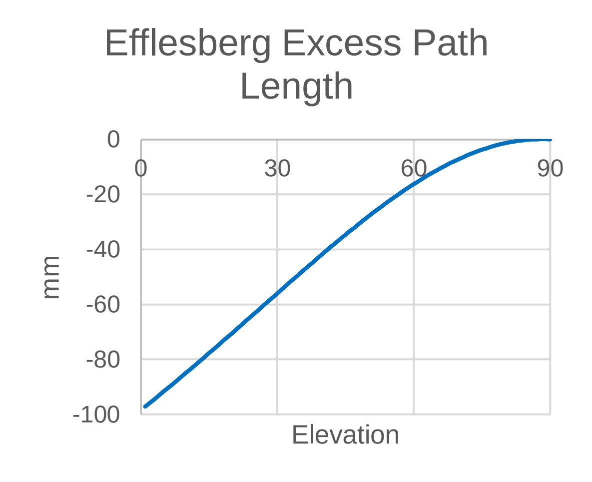












Models vary in sign and magnitude between different antennas.

Note on Yebes40M

YEBES40M, like Efflesberg, was designed to have homologous deformation—that is, it deformed under gravity but maintained its parabolic shape. However the location of the focus changed.

Prior to November 11, 2011, the Yebes40M sub-reflector was moved to optimize gain. This resulted in a purposeful change in path length with elevation.

After November 11 the focus was held fixed.

The model for Yebes40M is the difference in path length between the two cases.

Not a total gravitational deformation model, because there are other effects.

Including Effects in VLBI Analysis

Would like to have a general method for including gravitational deformation without having to link in a new subroutine for each antenna.

Our approach:

For each antenna have a table of (elevation, delay) from $1°$ to $90°$ at $1°$ increments. This table is read in at run time, and we use cubic splining to interpolate. Error in interpolation is << 0.1 mm.

Predicting Effect on Estimates

Approach:
For each antenna, do a least squares fit to the delay of the form:

$$\Delta L(el) \approx \frac{A}{\sin(el)} + C + U\sin(el)\,[+X\cos(el)]$$

We estimate the coefficients A, C, U and X, where the last term is optional.

The physical interpretation is:
A→ Change in Atmosphere
C→ Change in Clock
U→ Change in Up
X→ Change in axis offset (if estimated)

Results of Least Squares Fit

		ATM	CLK	UP
	WRMS	1/Sin(el)	1	Sin(el)
EFLESBERG	1.02	2.12	-117.16	114.33
GILCREEK	0.00	0.00	-2.40	2.40
MEDICINA	0.04	-0.13	-1.29	8.93
NOTO	0.15	0.11	-0.72	7.32
ONSALA60	0.08	-0.10	1.72	-5.07
YEBES40M	0.04	0.10	49.38	-49.53

Last column is ‘predicted’ change in Up due to applying model.

Fit Delay curve from 7-90 degrees.

Results of Least Squares Fit

		ATM	CLK	UP
	WRMS	1/Sin(el)	1	Sin(el)
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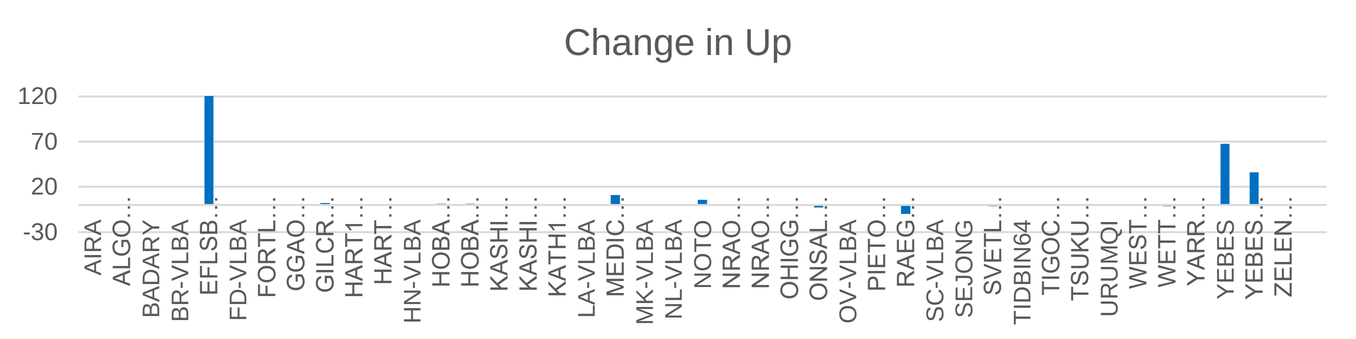
Last column is ‘predicted’ change in Up

		ATM	CLK	UP	AXIS
	WRMS	1/Sin(el)	1	Sin(el)	cos(el)
EFLESBERG	0.57	1.10	-98.74	99.20	-10.06
GILCREEK	0.00	0.00	-2.40	2.40	0.00
MEDICINA	0.03	-0.09	0.07	9.42	0.32
NOTO	0.02	-0.07	2.43	4.74	-1.72
ONSALA60	0.00	0.00	-0.06	-3.60	0.97
YEBES40M	0.02	0.05	50.16	-50.16	-0.42

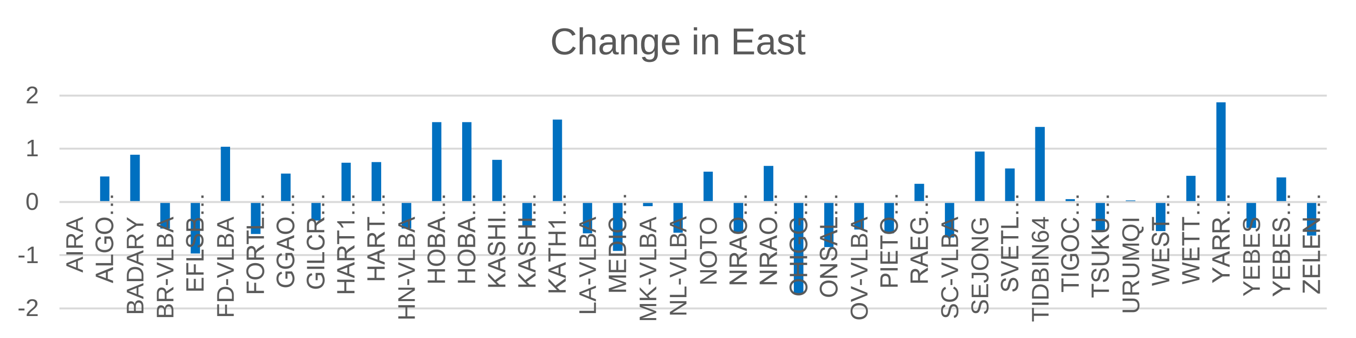
Including Axis offset can have a large effect on Up.

Change in Components

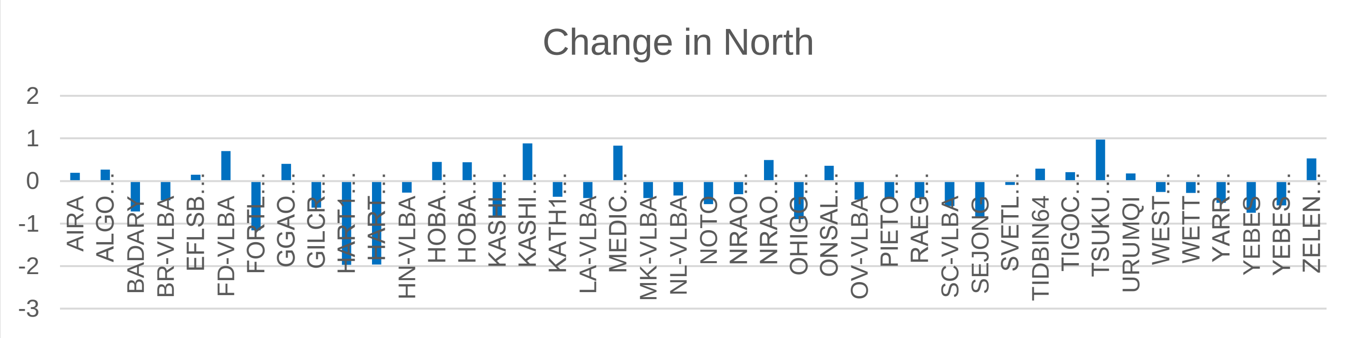
GSFC Default solution-Solution with gravity deformation



Most of the change is in Up



But East and North Change too!



Reason:
NNT constraints.

Stations in NNT/NNR Constraints

33 Stations that participated in:

Sessions >20

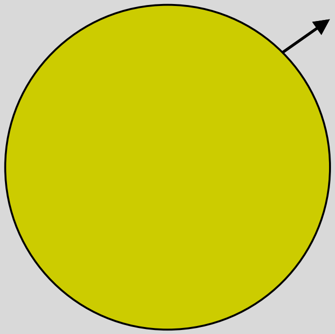
Span > 3 yr

Observations >1000

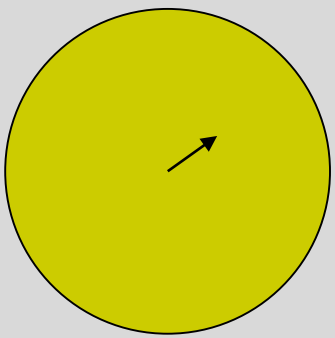
Excluded weak stations, and stations that had Earth quakes or episodic motion (Gilcreek, Tsukuba, Tigoconc, MK-VLBA…

ALGOPARK	BR-VLBA	DSS45	FD-VLBA	FORTLEZA
HARTRAO	HATCREEK	HAYSTACK	HN-VLBA	HOBART26
KASHIMA	KAUAI	KOKEE	KP-VLBA	LA-VLBA
MATERA	NL-VLBA	NOTO	NRAO20	NRAO85_3
NYALES20	ONSALA60	OV-VLBA	OVRO_130	PIETOWN
RICHMOND	SANTIA12	SC-VLBA	SESHAN25	VNDNBERG
WESTFORD	WETTZELL	SVETLOE	YEBES40M	HOBART12
KATH12M	YARRA12M	WARK12M		

NNT Constraint shifts the origin



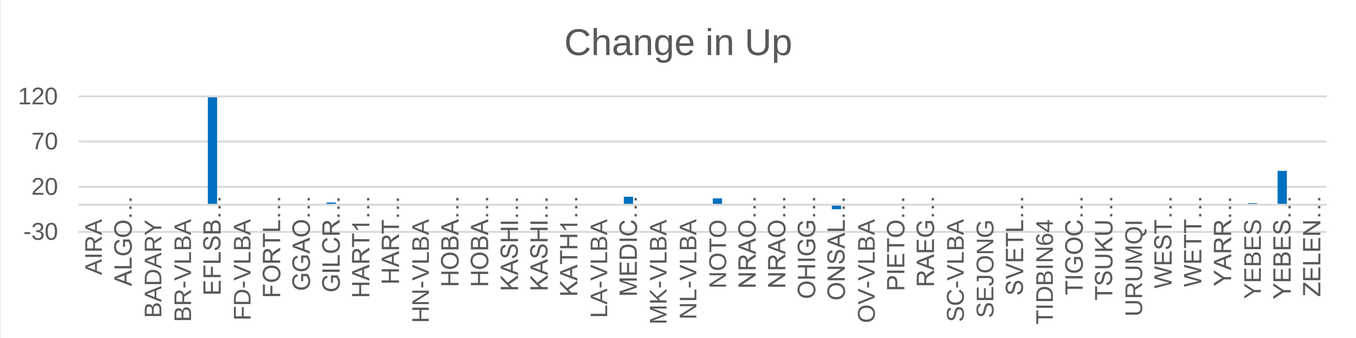
A change in “Up” at Noto, YEBES40M

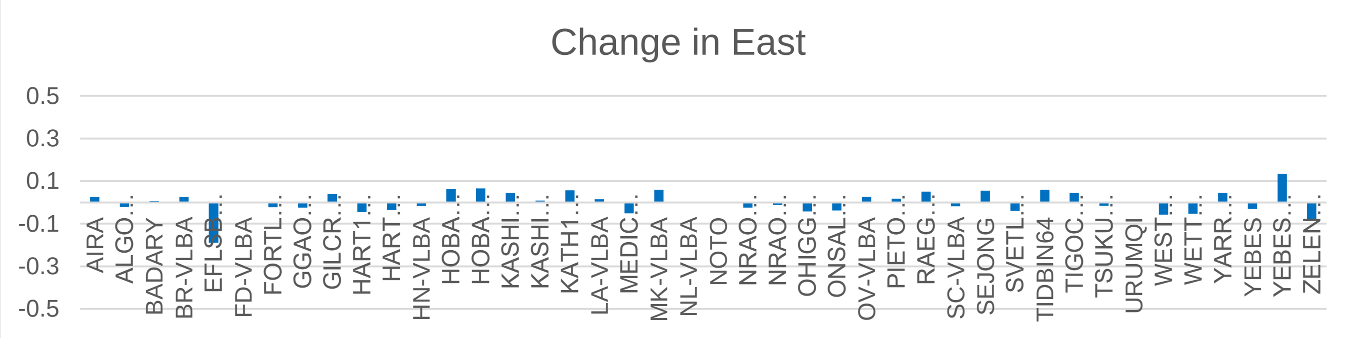


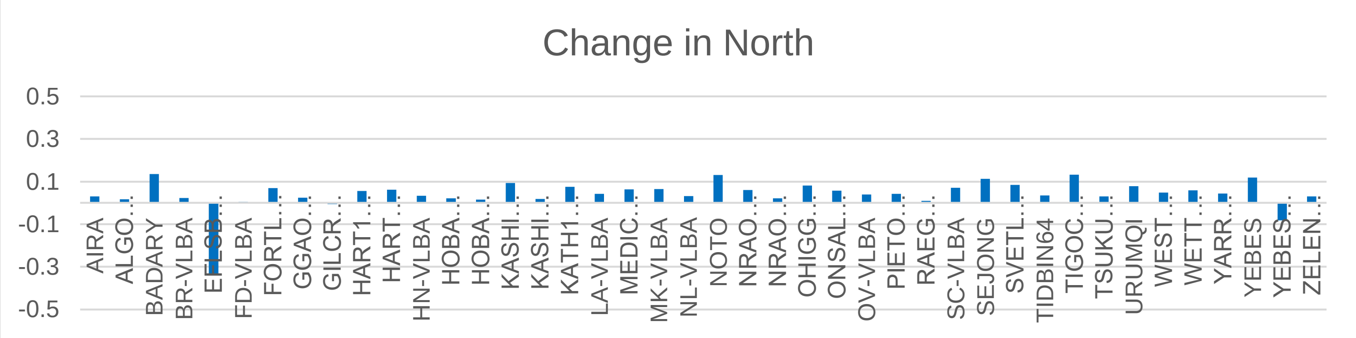
Looks like a change in the horizontal elsewhere

Fix: Remove stations from NNR/NNT

New Default Solution-Solution with gravity deformation





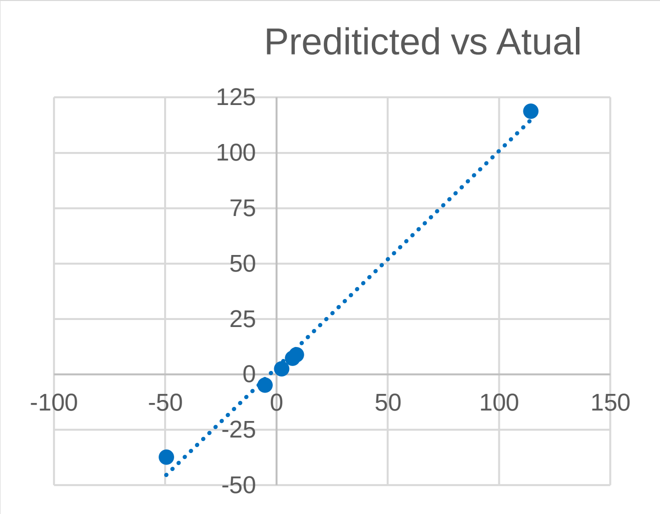


In new solution stations with deformation models removed from NNT/NNR constraints.

This reduces change in East and North components.

Predicted and actual change in Up

	Size(M)	Predicted (mm)	Actual (mm)
EFLESBERG	100	114.3	118.70
GILCREEK	26	2.4	2.46
MEDICINA	32	8.9	8.87
NOTO	32	7.3	7.26
ONSALA60	20	-5.1	-4.92
YEBES40M	40	-49.5	-37.44



Sarti, Abbondanza, Petrov and Negusini (2011) found a change in local Up of:

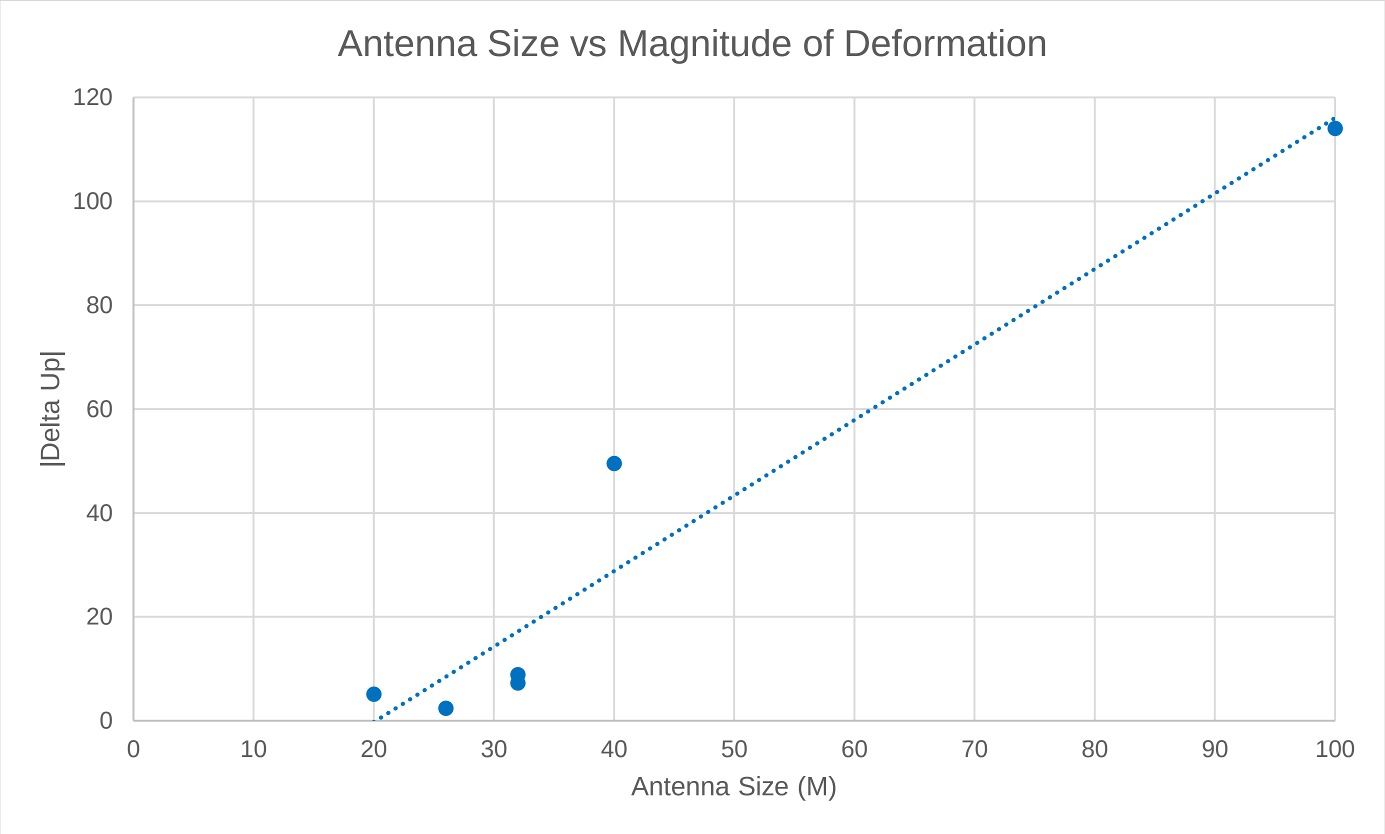
8.9 for Medicina

6.7 for Noto

For most antennas there is good agreement between predicated and actual change in local up.

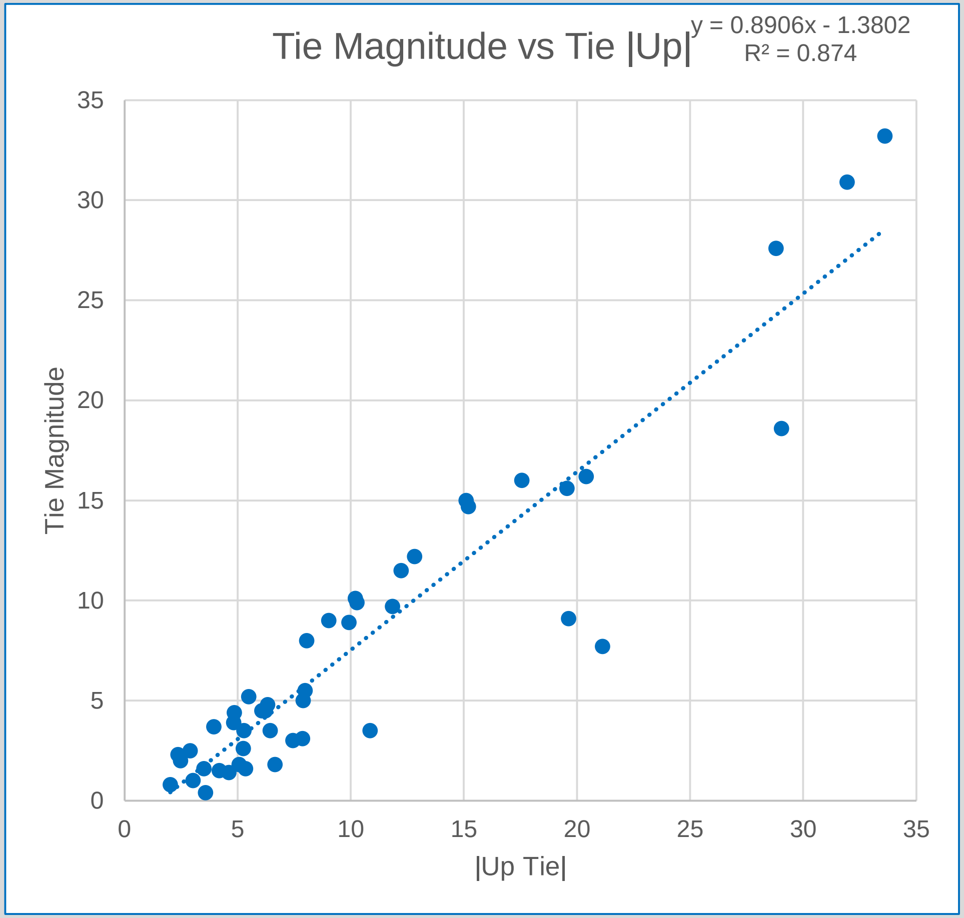
The notable exception is YEBES40M which I will discuss later.

Effect is larger for larger antennas



Expect to be small for VGOS antennas which are ~12-13M

GPS VLBI Tie Discrepancy



90% of the GPS-VLBI tie discrepancy is due to differences in Up.

This can be due to:

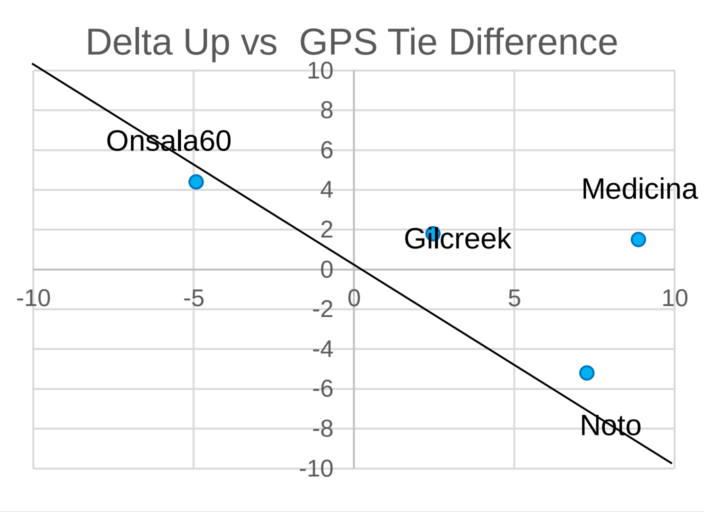
a) surveying error;
b) GPS phase errors;
c) VLBI antenna deformation;
d) something else.

From ITRF2014

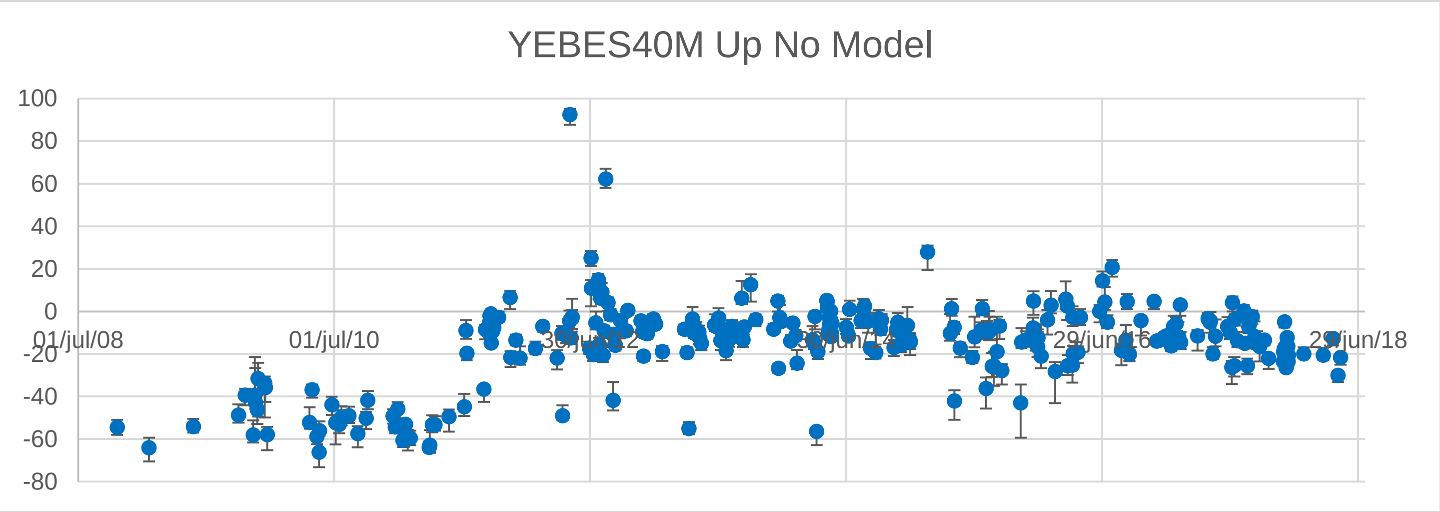
Do the models reduce tie errors?

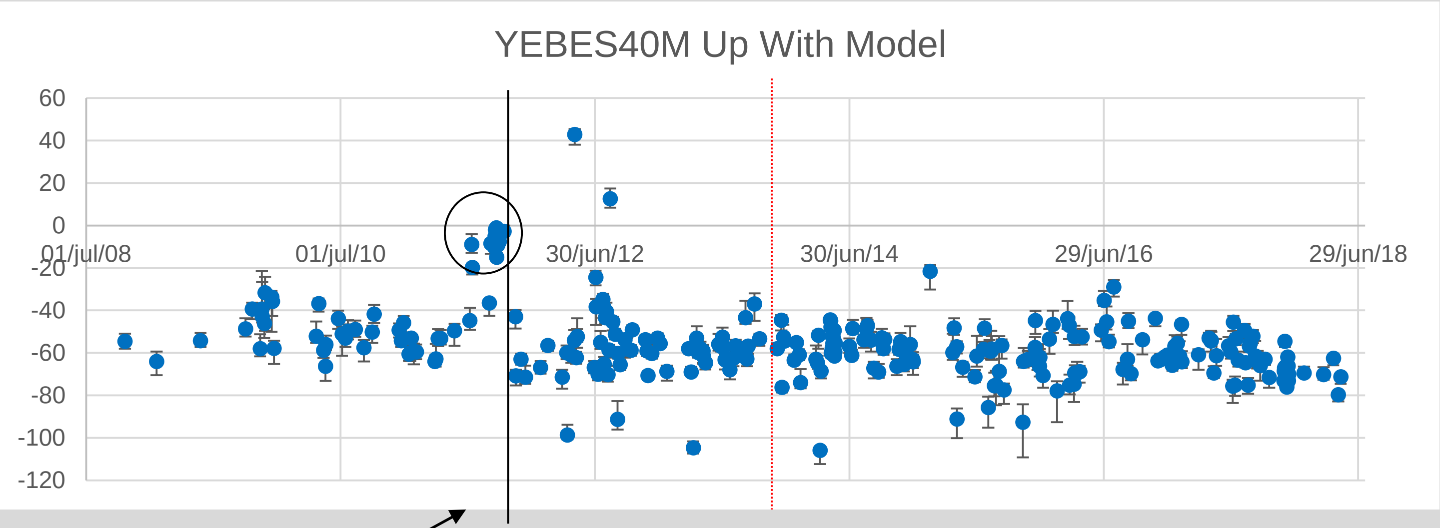
	Size(M)	Predicted (mm)	Actual (mm)	VLBI-GPS Up Tie Difference(mm)
EFLESBERG	100	114.3	118.70	
GILCREEK	26	2.4	2.46	1.8
MEDICINA	32	8.9	8.87	1.5
NOTO	32	7.3	7.26	-5.2
ONSALA60	20	-5.1	-4.92	4.4
YEBES40M	40	-49.5	-37.44	

For some antennas (ONSALA60, NOTO)
DeltaUp ~ GPS Tie



Back to Yebes40M





Model applied.

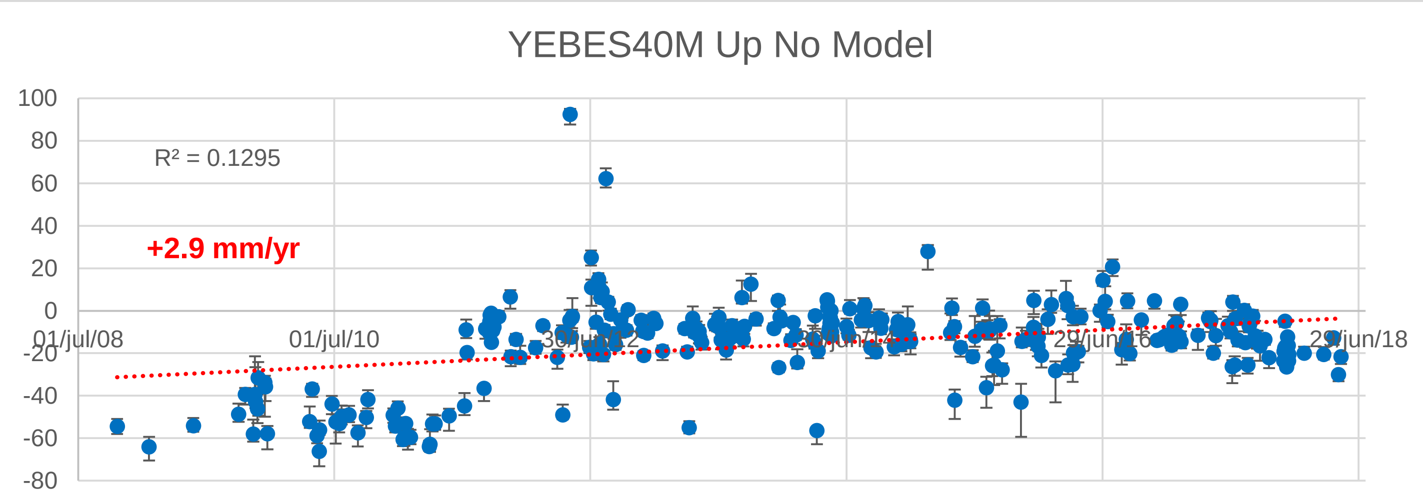
The model applies only after Nov 11, 2011.

Applying the model removes (most of) the discontinuity at Nov 11, 2011.

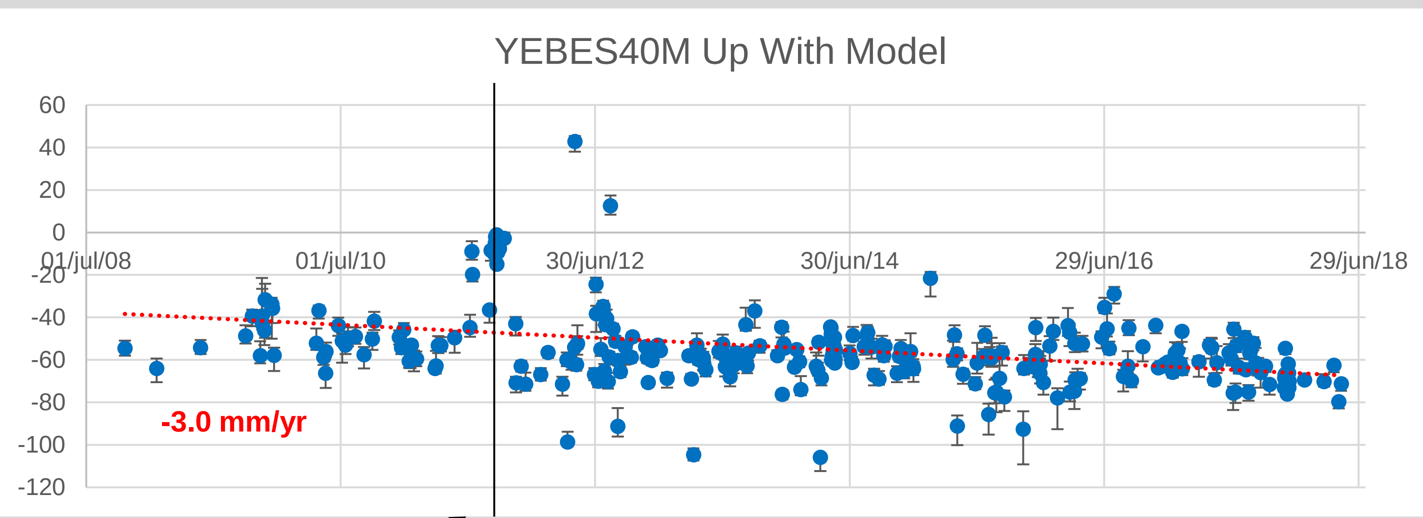
Axel Nothnagel noticed this first, and presented results at the 2014 IVS General Meeting.

He had data through 2013 (red line).

Up Slope Before and After



Changing procedure introduces change in slope.



Applying the model reduces the discontinuity, and the slope is now downwards.

Model applied.

Issue: Velocity Constraint

Our default solution constrains YEBES, YEBES40M and RAEGYEB to all have the same velocity. Seems reasonable since they are all close (~300 m).

		VelCon					
		Est	Sigma				
RAEGYEB	U	9.17	0.75				
RAEGYEB	E	-4.73	1.02				
RAEGYEB	N	8.17	1.00				
YEBES	U	-69.29	2.52				
YEBES	E	-3.27	1.15				
YEBES	N	8.17	1.14				
YEBES40M	U	-5.15	0.54				
YEBES40M	E	-1.41	1.01				
YEBES40M	N	9.81	0.98				

Velocity Constraint Issue at YEBES

Our default solution constrains YEBES, YEBES40M and RAEGYEB to all have the same velocity. Seems reasonable since they are all close (~300 m).

Introducing the deformation model in the default solution results in changes in the positions of YEBES and RAEGYEB

		VelCon		VelCon& GravDef			
		Est	Sigma	Est	Sig	Dif	|Dif/Sig|
RAEGYEB	U	9.17	0.75	19.06	0.75	-9.89	13.19
RAEGYEB	E	-4.73	1.02	-5.07	1.02	0.34	0.33
RAEGYEB	N	8.17	1.00	8.57	1.00	-0.40	0.40
YEBES	U	-69.29	2.52	-136.91	2.52	67.62	26.83
YEBES	E	-3.27	1.15	-2.78	1.15	-0.49	0.43
YEBES	N	8.17	1.14	8.92	1.14	-0.75	0.66
YEBES40M	U	-5.15	0.54	-41.10	0.54	35.95	66.57
YEBES40M	E	-1.41	1.01	-1.87	1.01	0.46	0.46
YEBES40M	N	9.81	0.98	10.38	0.98	-0.57	0.58

Surprise!

Expect this change

Velocity Constraint Issue at YEBES(2)

Removing the velocity constraint removes most of the change in position of Up.

		NoVelCon		NoVelCon GravDeform			
		Est	Sigma	Est	Sig	Dif	|Dif/Sig|
RAEGYEB	U	9.20	3.42	9.28	3.42	-0.08	0.02
RAEGYEB	E	1.14	1.53	1.09	1.53	0.05	0.03
RAEGYEB	N	11.54	1.52	11.53	1.52	0.01	0.01
YEBES	U	-112.74	12.38	-114.65	12.38	1.91	0.15
YEBES	E	-4.13	2.75	-4.10	2.75	-0.03	0.01
YEBES	N	17.69	3.03	17.57	3.03	0.12	0.04
YEBES40M	U	-4.90	0.59	-42.34	0.59	37.44	63.46
YEBES40M	E	-1.38	1.13	-1.52	1.13	0.14	0.12
YEBES40M	N	11.50	1.15	11.59	1.15	-0.09	0.08

← Was -67.72

Similar problems if you put stations with deformation models in NNT constraints.

Gravity Deformation Improves Velocity Consistency

No Velocity constraint, no deformation model

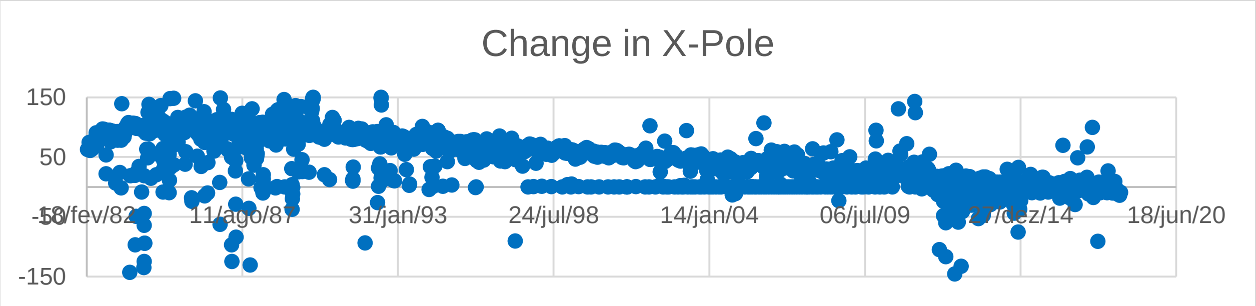
	YEBES		YEBES40M		Diff	
	Est	σ	Est	σ	Δ	Δ/σ
U	-2.2	0.9	1.08	0.08	-3.28	3.63
E	18.87	0.19	18.95	0.05	-0.08	0.41
N	17.52	0.21	16.94	0.06	0.58	2.71

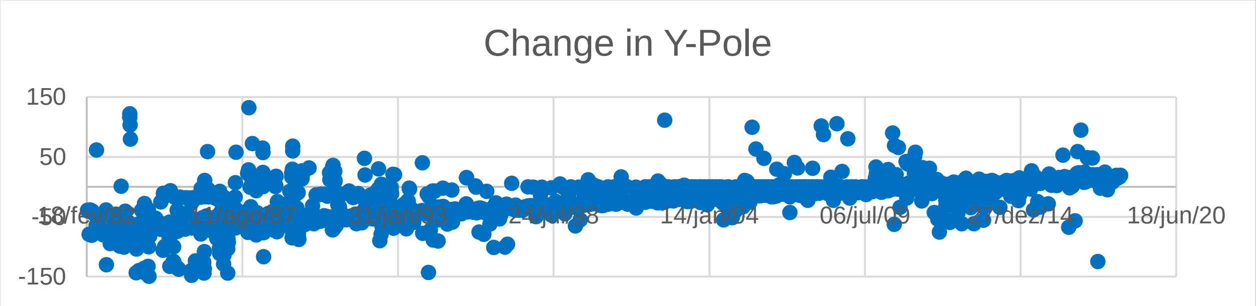
No Velocity constraint, with deformation model

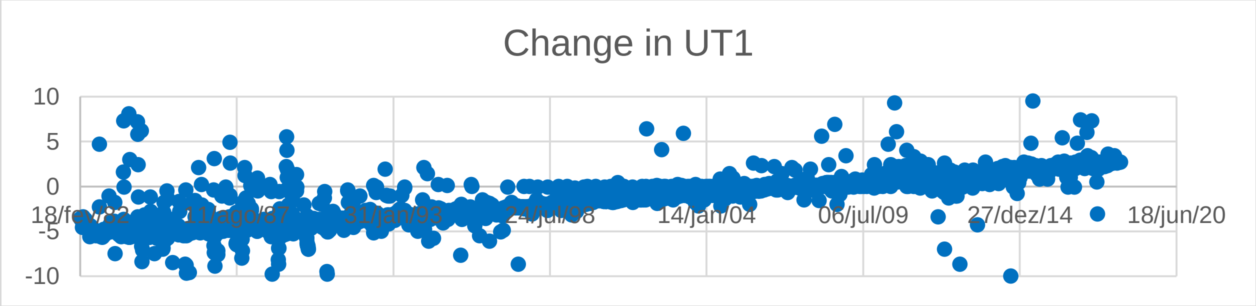
	YEBES		YEBES40M		Diff	
	Est	σ	Est	σ	Δ	Δ/σ
U	-2.31	0.9	-4.05	0.08	1.74	1.92
E	18.87	0.19	19.00	0.05	-0.13	0.67
N	17.51	0.21	16.97	0.06	0.54	2.53

YEBES40M Up changes sign, and is closer to Yebes Up

Effect on EOP of Changing NNR/NNT







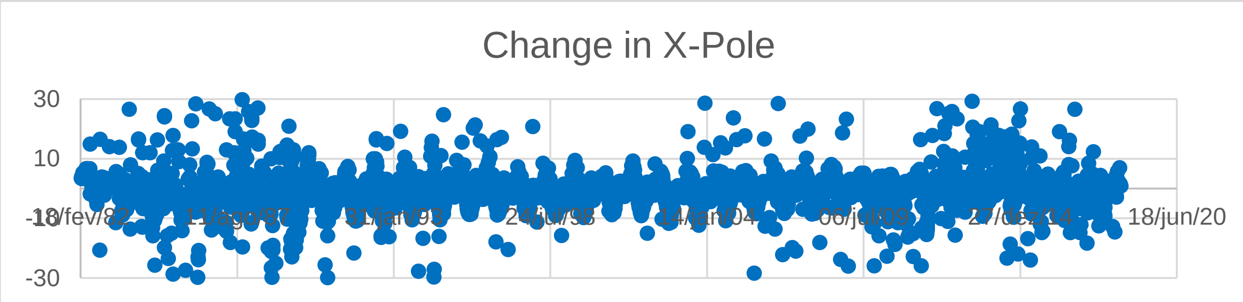
Solution 1: Default GSFC solution.

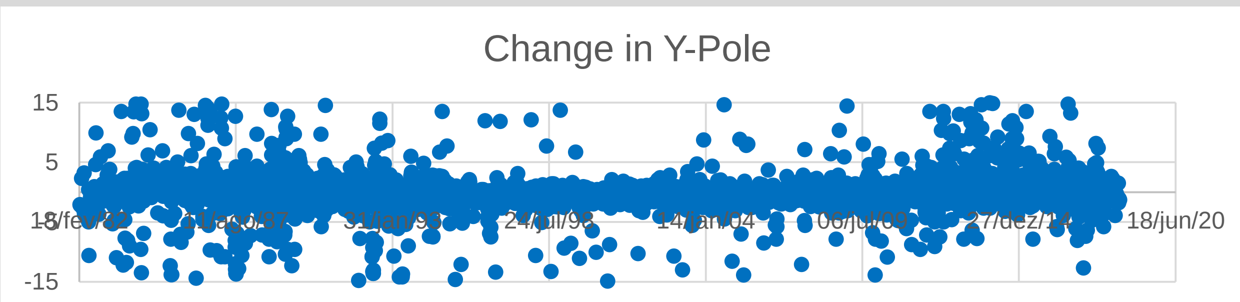
Solution 2: Remove stations with gravity deformation models from NNT/NNR constraints.

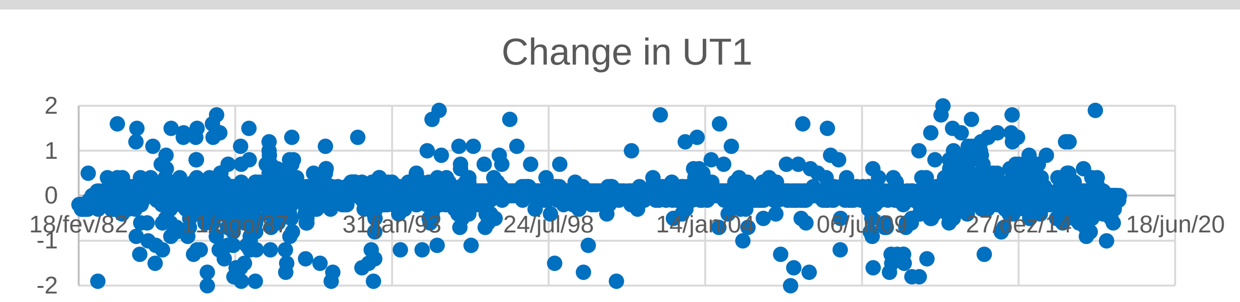
Stations removed:
Efflesberg
Gilcreek
Medicina
Noto
Onsala60
Yebes40M

Removing stations changes the frame and effects EOP.

Effect on EOP of Deformation Models





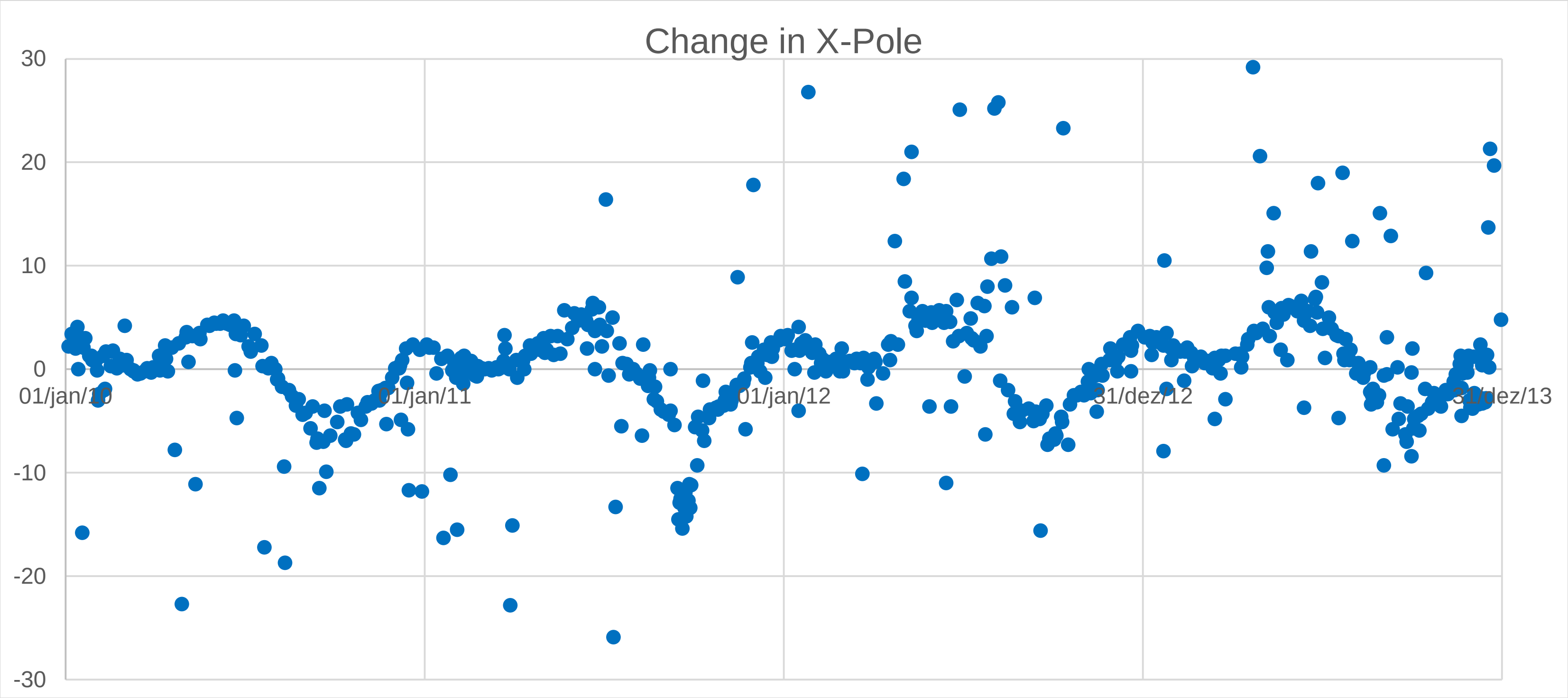


Difference between two solutions:

With and without gravity deformation.

Both solutions exclude:
Effelsberg
Gilcreek
Medicina
Noto
Onsala60
Yebes40M

Close up of X-pole



Origin of annual signal is unclear.

Conclusions

- Gravitational deformation of VLBI antennas leads to an elevation dependent change in the delay.
- This will lead to changes in the estimates of Up, Clock and Atmosphere at a station.
- Minimal effect on the estimate of E,N.
- These changes can be large (up to 100mm for Efflesberg!).
- Typical values ~0-10 mm.
- Changing solution changes EOP.
- Since gravitational deformation affects Up, it affects the scale.
- The only fix is to measure or model the VLBI antennas.

Conclusions

ITRF2020 will include Deformation Models for antennas that have models of.

The NASA Space Geodesy Project plans to measure the deformation of NASA SGP antennas.

As the IVS Analysis Coordinator, I encourage all other institutions to do the same.