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GPS receiver calibration: a tutorial

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Bruce Warrington, NMIA

measurement.gov.au

Purpose

To introduce the draft protocol for calibration of GPS receiver delays and provide sufficient information to:

- Give participating laboratories confidence in the reported delays
- Allow laboratories to independently analyse data obtained during a comparison
- Allow laboratories to use the same protocol to calibrate other receivers they may operate

Outline

- Introduction to the draft technical protocol for calibration of L1 delays using C/A measurements
- Sample data analysis
- Diagnostics and checks
- An exercise
- Resources

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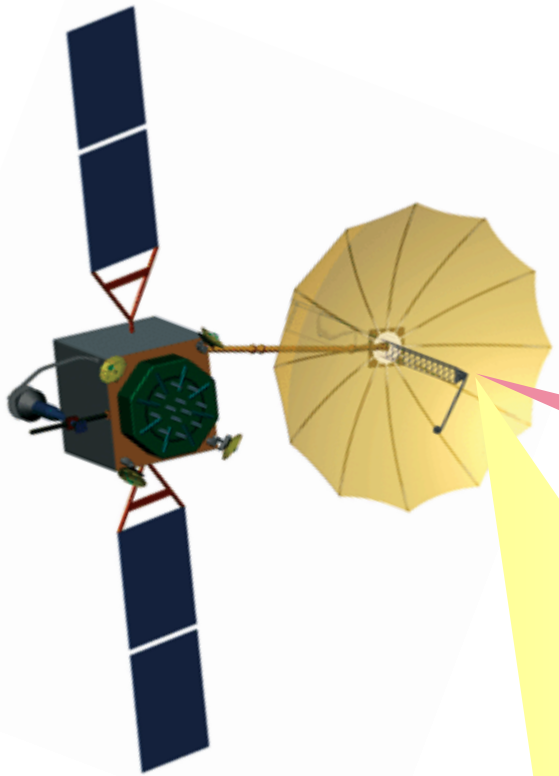
Reminder: basic GPS signals



L1 1575.42 MHz

C/A code “coarse acquisition”

P(Y)-code (encrypted)

L2 1227.60 MHz

P(Y)-code (encrypted)

New signals eg L2C a new civilian code available at L2

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Reminder: CGGTTS files

```
GGTTS GPS DATA FORMAT VERSION = 01
REV DATE = 1997-11-04
RCVR = NML Topcon Euro-80 L1/L2
CH = 12
IMS = NML Euro-80 L1/L2 Pseudorange differences
LAB = NML Australia
X = -4648200.298 m
Y = +2560484.035 m
Z = -3526505.358 m
FRAME = ITRF93
COMMENTS = NML Lindfield - Primary system.
INT DLY = 46.5 ns
CAB DLY = 75.9 ns
REF DLY = 68.9 ns
REF = 360340
CKSUM = A6

PRN CL  MJD  STTIME TRKL ELV AZTH   REFSV      SRSV     REFGPS    SRGPS  DSG IOE MDTR SMDT MDIO SMDI MSIO SMSI ISG CK
            hhmmss   s  .1dg .1dg    .1ns     .1ps/s     .1ns   .1ps/s .1ns      .1ns.1ps/s.1ns.1ps/s.1ns.1ps/s.1ns
 30 FF 53249 002600  780 390 2257    -5507621    +7       +5062    -24   21 104  129  -18   80   -8   41  +42  30 3D
 24 FF 53249 002600  780 650 1383     -534562   -35       +5185     -5    5 000   90   +6   60   +4   28  +30  11 F3
 10 FF 53249 002600  780 306  384     -493148   -19       +5135    -13   30 104  159  -31  105  -13  119   +9  41 4C
  6 FF 53249 002600  780 160 2559    -4081768  -199       +5087    +57   33 058  292  -82  125  -11  132  +10  81 AA
  5 FF 53249 002600  780 741 2373     -463113   +15       +5093    +33    6 141   84   -3   57   -0   36  +19   6 EC
 17 FF 53249 002600  780 792 3303    +1408508   +98       +5156    +11    6 072   83   -2   57   -0   33  -23   7 18
  4 FF 53249 002600  780 265 1360    +2749375   +50       +5131   -109   29 179  181  +43  104  +15   78  +86  61 8E
  9 AC 53249 002600  780 271 3258      +30402   +17       +5202     -1   25 047  178  +37  108  +18   77   -2  38 1
```

modelled troposphere

modelled ionosphere

measured ionosphere

REFSV is corrected for: geometric delay; **modelled ionosphere**; **modelled troposphere**; Sagnac effect; relativistic effect due to the eccentricity of the GPS satellite's orbit; L1-L2 broadcast correction; INT, CAB and REF delays

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Draft analysis protocol for multichannel GPS receivers

1. Obtain precise antenna co-ordinates for the travelling receiver.
2. Regenerate CCTF data for the travelling system.
3. Filter the tracks, discarding any which do not meet defined quality criteria.
4. Match the tracks and form REF-SV differences.
5. Linear fits to REF-SV are performed.
6. The raw offset as obtained from the linear fit is corrected for any difference between the delays recorded in the CCTF file and those reported by the host laboratory.

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Protocol: antenna coordinates

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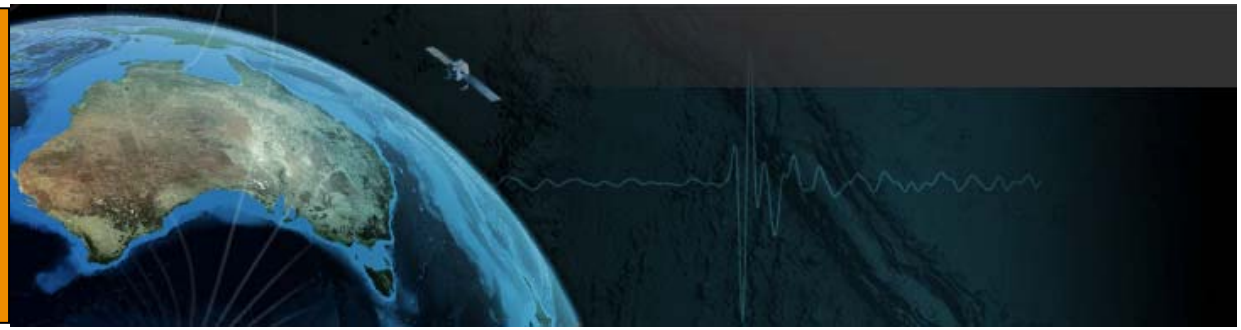
Geoscience Australia



http://www.ga.gov.au/earth-monitoring/geodesy/auspos-online-gps-processing-service.html

3 Computed Coordinates, ITRF2000

All computed coordinates are based on the IGS realisation of the ITRF2000 reference frame, provided by the IGS cumulative solution. All the given ITRF2000 coordinates refer to a mean epoch of the site observation data. All coordinates refer to the Ground Mark.

3.1 Cartesian, ITRF2000

	X(m)	Y(m)	Z(m)	ITRF2000 @
shao	-2831733.512	4675665.953	3275369.410	2005/03/11
suwn	-3062022.870	4055448.015	3841818.249	2005/03/11
daej	-3120041.983	4084614.882	3764026.897	2005/03/11
APMP	-3120134.365	4085468.256	3763042.462	2005/03/11

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X = -4648200.298 m
Y = +2560484.035 m
Z = -3526505.358 m
FRAME = ITRF93

Upload RINEX observation files to eg AUSPOS to obtain precise coordinates

Update CCTF header/configuration files with new antenna coordinates

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Protocol: reprocess raw data

raw GPS data

TI measurements

CCTF

... details may vary

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Protocol: filtering

Discard the track if any of these fields is tagged ‘bad’ with a value of 999

PRN	CL	MJD	STTIME	TRKL	ELV	AZTH	REFSV	SRSV	REFGPS	SRGPS	DSG	IOE	MDTR	SMDT	MDIO	SMDI	MSIO	SMSI	ISG	CK
			hhmmss	s	.1dg	.1dg	.1ns	.1ps/s	.1ns	.1ps/s	.1ns		.1ns	.1ps/s	.1ns	.1ps/s	.1ns	.1ps/s	.1ns	
30	FF	53249	002600	780	390	2257	-5507621	+7	+5062	-24	21	104	129	-18	80	-8	41	+42	30	3D
24	FF	53249	002600	780	650	1383	-534562	-35	+5185	-5	5	000	90	+6	60	+4	28	+30	11	F3
10	FF	53249	002600	780	306	334	-493148	-19	+5135	-13	30	104	159	-31	105	-13	119	+9	41	4C
6	FF	53249	002600	780	160	2559	-4081768	-199	+5087	+57	33	058	292	-82	125	-11	132	+10	81	AA
5	FF	53249	002600	780	741	2373	-463113	+15	+5093	+33	6	141	84	-3	57	-0	36	+19	6	EC
17	FF	53249	002600	780	792	3303	+1408508	+98	+5156	+11	6	072	83	-2	57	-0	33	-23	7	18
4	FF	53249	002600	780	265	1360	+2749375	+50	+5131	-109	29	179	181	+43	104	+15	78	+86	61	8E
9	AC	53249	002600	780	271	3258	+30402	+17	+5202	-1	25	047	178	+37	108	+18	77	-2	38	1

The track length must be the full 780 s

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Protocol: match tracks

Host receiver

PRN	CL	MJD	STTIME hhmmss	TRKL s	ELV .1dg	AZTH .1dg	REFSV .1ns
4	FF	53170	001000	780	148	264	+1767377
5	FF	53170	001000	780	207	3064	-347030
17	FF	53170	001000	780	229	3098	+433616
10	FF	53170	001000	780	673	2727	-455681
7	FF	53170	001000	780	462	774	-5043058
26	FF	53170	001000	780	162	1959	-1165558
28	FF	53170	001000	780	225	1543	-346695
29	FF	53170	001000	780	275	1848	-2251213
4	FF	53170	002600	780	133	329	+1767556

Travelling receiver

PRN	CL	MJD	STTIME hhmmss	TRKL s	ELV .1dg	AZTH .1dg	REFSV .1ns
7	FF	53170	001000	780	470	788	-5043243
26	FF	53170	001000	780	176	1970	-1165797
24	FF	53170	001000	780	253	3493	-344492
17	FF	53170	001000	780	240	3110	+433448
4	FF	53170	001000	780	160	278	+1767320
28	FF	53170	001000	780	235	1560	-346695
5	FF	53170	001000	780	220	3075	-347208
29	FF	53170	001000	780	290	1859	-2251418
10	FF	53170	001000	780	680	2742	-455828

Form the set of differences REF–SV

$$\varepsilon(t) = [\text{REF–SV}]_A(t) + [\text{MDIO}]_A(t) - [\text{REF–SV}]_B(t) - [\text{MDIO}]_B(t)$$

The modelled ionosphere MDIO is removed since it can add noise

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Protocol: linear fits

- Calculate the mean offset $\varepsilon(t)$ by performing a linear regression
- The linear term accounts for any slow variation in the offset between the two receivers
- The regression is performed using both an unweighted fit and a fit weighted by the DSG value for a track

PRN	CL	MJD	STTIME	TRKL	ELV	AZTH	REFSV	SRSV	REFGPS	SRGPS	DSG	IOE	MDTR	SMDT	MDIO	SMDI	MSIO	SMSI	ISG	CK
			hhmmss	s	.1dg	.1dg	.1ns	.1ps/s	.1ns	.1ps/s	.1ns		.1ns	.1ps/s	.1ns	.1ps/s	.1ns	.1ps/s	.1ns	
30	FF	53249	002600	780	390	2257	-5507621	+7	+5062	-24	21	104	129	-18	80	-8	41	+42	30	3D
24	FF	53249	002600	780	650	1383	-534562	-35	+5185	-5	5	000	90	+6	60	+4	28	+30	11	F3
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- Analysis of many data sets shows good agreement between the weighted and unweighted fits
- An unweighted fit is therefore used
- The offset is evaluated at the midpoint of the data set

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Protocol: correct for delays

$$[\text{REF–SV}] = (\text{REF–SV})_{\text{Raw}} - [\text{INT DLY}] - [\text{CAB DLY}] + [\text{REF DLY}]$$

$$[\text{REF–SV}]' = [\text{REF–SV}] + \delta$$
$$\delta = -[\text{INT DLY}]_{\text{Reported}} + [\text{INT DLY}]_{\text{Internal}} - [\text{CAB DLY}]_{\text{Reported}} - \delta_X + [\text{CAB DLY}]_{\text{Internal}} + [\text{REF DLY}]_{\text{Reported}} - [\text{REF DLY}]_{\text{Internal}}$$

Correct [REF-SV] for reported delays

$$\varepsilon(t)' = [\text{REF–SV}]_A(t)' - [\text{REF–SV}]_B(t)'$$
$$= ([\text{REF–SV}]_A(t) + \delta_A) - ([\text{REF–SV}]_B(t) + \delta_B)$$
$$= \varepsilon(t) + \delta_A - \delta_B$$

Define the corrected [REF-SV] difference

$$\overline{\varepsilon(t)}'' = \overline{\varepsilon(t)}' + \delta_A - \delta_B$$
$$\equiv \Delta$$

Form the mean, corrected [REF-SV] difference

$$\varepsilon(t)'' = \varepsilon(t)' - \Delta \text{ so that } \overline{\varepsilon(t)}'' = 0$$
$$[\text{REF–SV}]_A'' = [\text{REF–SV}]_A(t)' - [\text{INT DLY}]_{A,\text{True}} + [\text{INT DLY}]_{A,\text{Reported}}$$
$$[\text{INT DLY}]_{A,\text{True}} = [\text{INT DLY}]_{A,\text{Reported}} + \Delta$$

Correct the reported internal delay

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Example: APMP round 2

Travelling receiver

Topcon Euro 80

dual-frequency receiver

Host receiver (KRISS)

Topcon Euro 80

dual-frequency receiver

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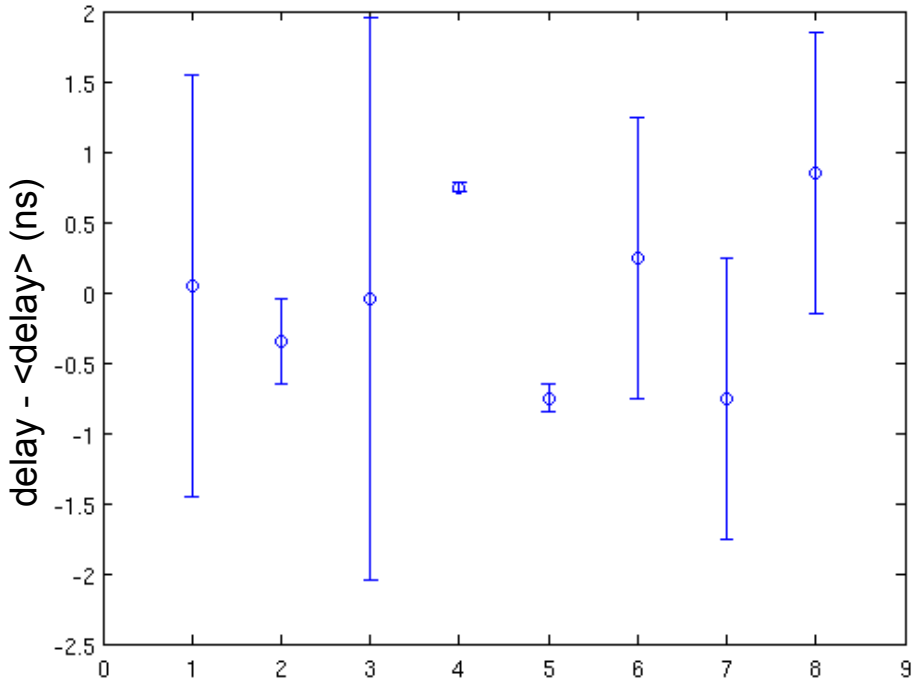
An aside: cable delays

Measurements of APMP antenna cable by host laboratories

Method	Delay (ns)
Network analyzer	159.0 ±1.5
Insertion delay	158.6 ± 0.3
Cable reversal	158.9 ± 2
Insertion delay	159.7 ± 0.03
Network analyzer	158.2 ± 0.1
1 pps delay	159.2 ± 1
1 pps delay	158.2 ± 1
1 pps delay	159.8 ± 1



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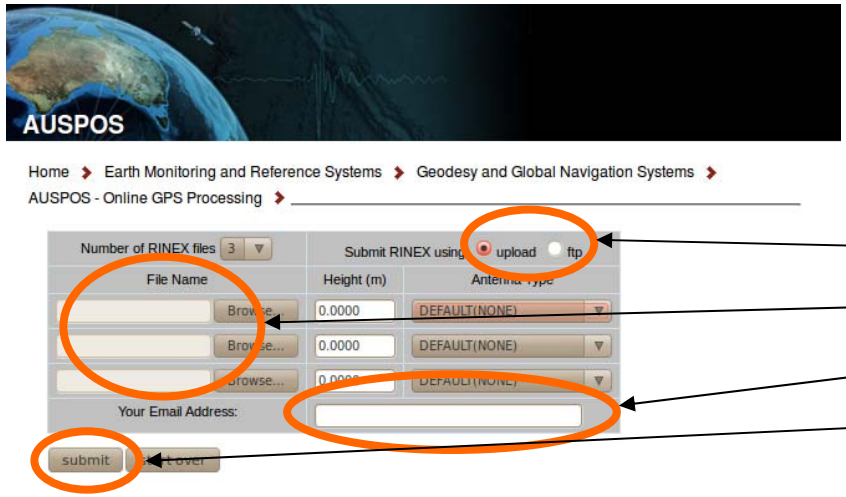
Example: update antenna coordinates

http://www.ga.gov.au/earth-monitoring/geodesy/auspos-online-gps-processing-service.html

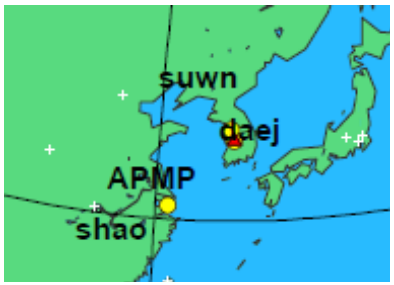


Select upload method

Select RINEX observation files to upload

Enter email address

Submit



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shao	-2831733.513	4675665.953	3275369.410	2005/03/12
suwn	-3062022.870	4055448.015	3841818.249	2005/03/12
daej	-3120041.983	4084614.882	3764026.897	2005/03/12
APMP	-3120134.366	4085468.253	3763042.461	2005/03/12
APMP	0.002 m	0.007 m	0.002 m	RMS

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Example: reprocess raw data

raw GPS data

TI measurements

CCTF

... details may vary

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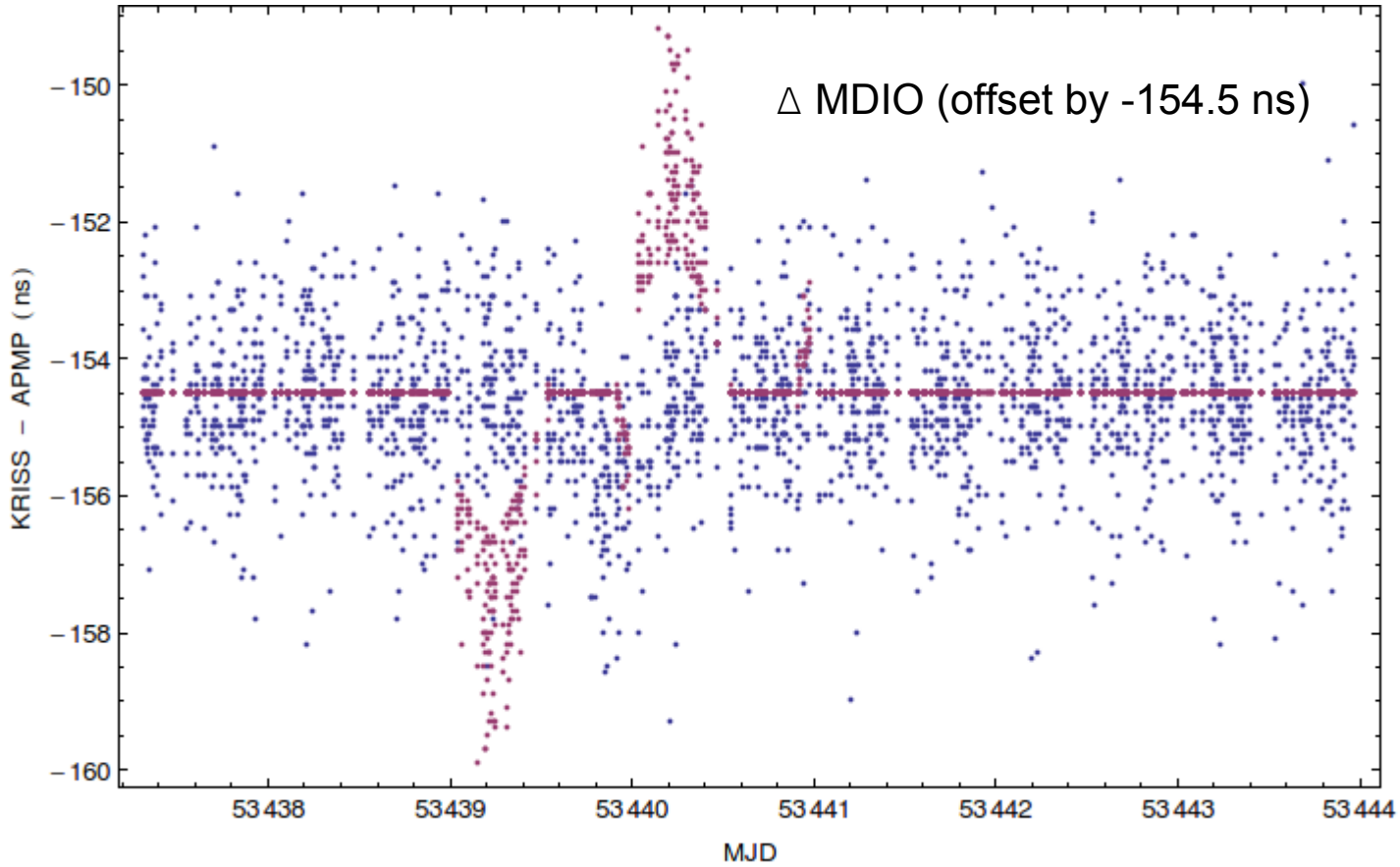
Example: filter and match tracks

REF-SV with modelled ionosphere removed



KRISS: 2403 of 2566 tracks ok

APMP: 2381 of 2496 tracks ok

2305 matched tracks from 7 days of data

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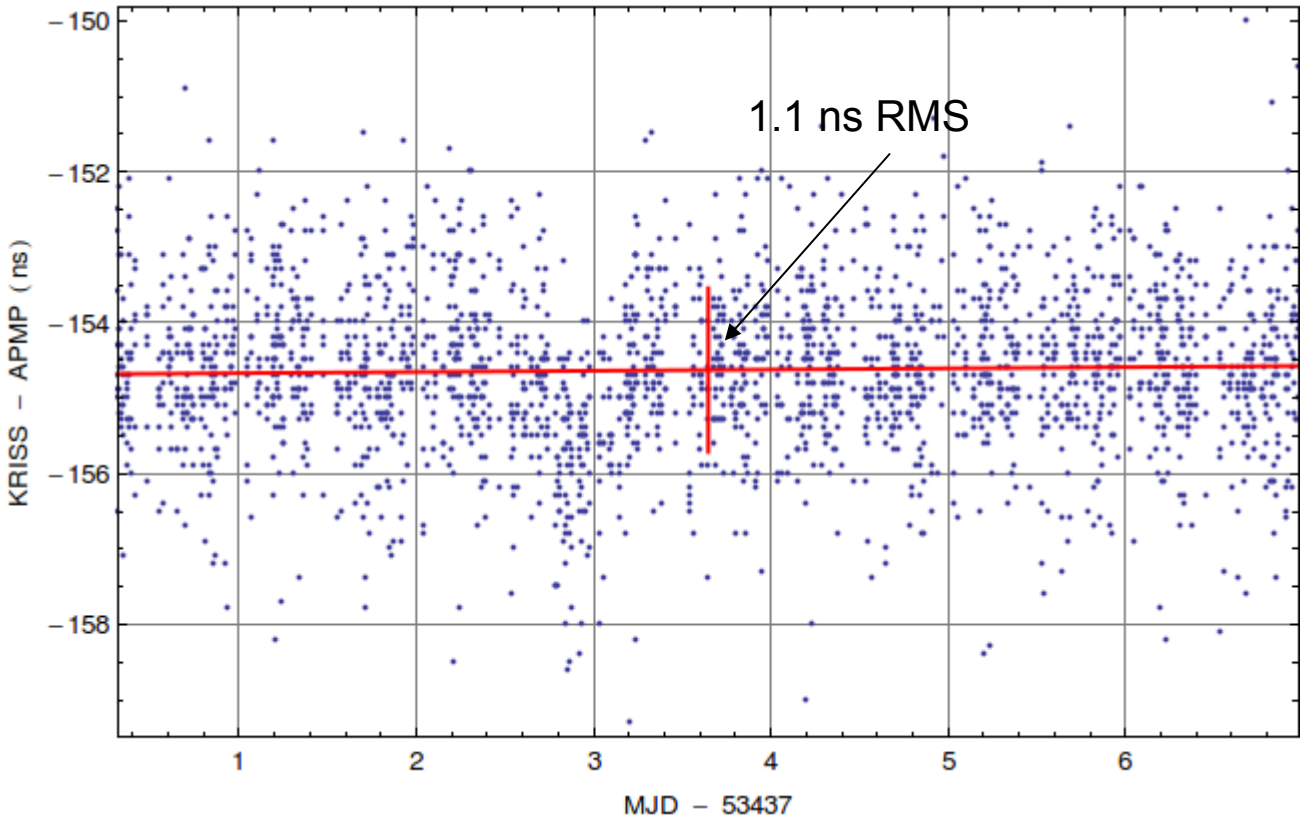
Example: linear fits



	Offset (ns)	Slope (ps/day)
Unweighted fit	-154.6	16 ± 12
DSG weighted fit	-154.6	16 ± 9

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Example: correct for delays

$$[\text{REF}-\text{SV}]' = [\text{REF}-\text{SV}] + \delta$$

$$\delta = -[\text{INT DLY}]_{\text{Reported}} + [\text{INT DLY}]_{\text{Internal}} - [\text{CAB DLY}]_{\text{Reported}} - \delta_X + [\text{CAB DLY}]_{\text{Internal}} + [\text{REF DLY}]_{\text{Reported}} - [\text{REF DLY}]_{\text{Internal}}$$

Rx	Internal	Reported	δ
KRISS	INT DLY = 36.5 ns CAB DLY = 114.8 ns REF DLY = 22.4 ns	INT DLY = 36.5 ns CAB DLY = 114.8 ns REF DLY = 22.4 ns	$\delta_A = 0$ ns
APMP	INT DLY = 0.0 ns CAB DLY = 0.0 ns REF DLY = 0.0 ns	INT DLY = 33.1 ns CAB DLY = 159.8 ns REF DLY = 20.8 ns	$\delta_B = -172.1$ ns

$$\overline{\varepsilon(t)''} = \overline{\varepsilon(t)'} + \delta_A - \delta_B \equiv \Delta$$

Final result:

$$\Delta = -154.6 + 0 + 172.1 = 17.5 \text{ ns}$$

This is added to the reported delay.

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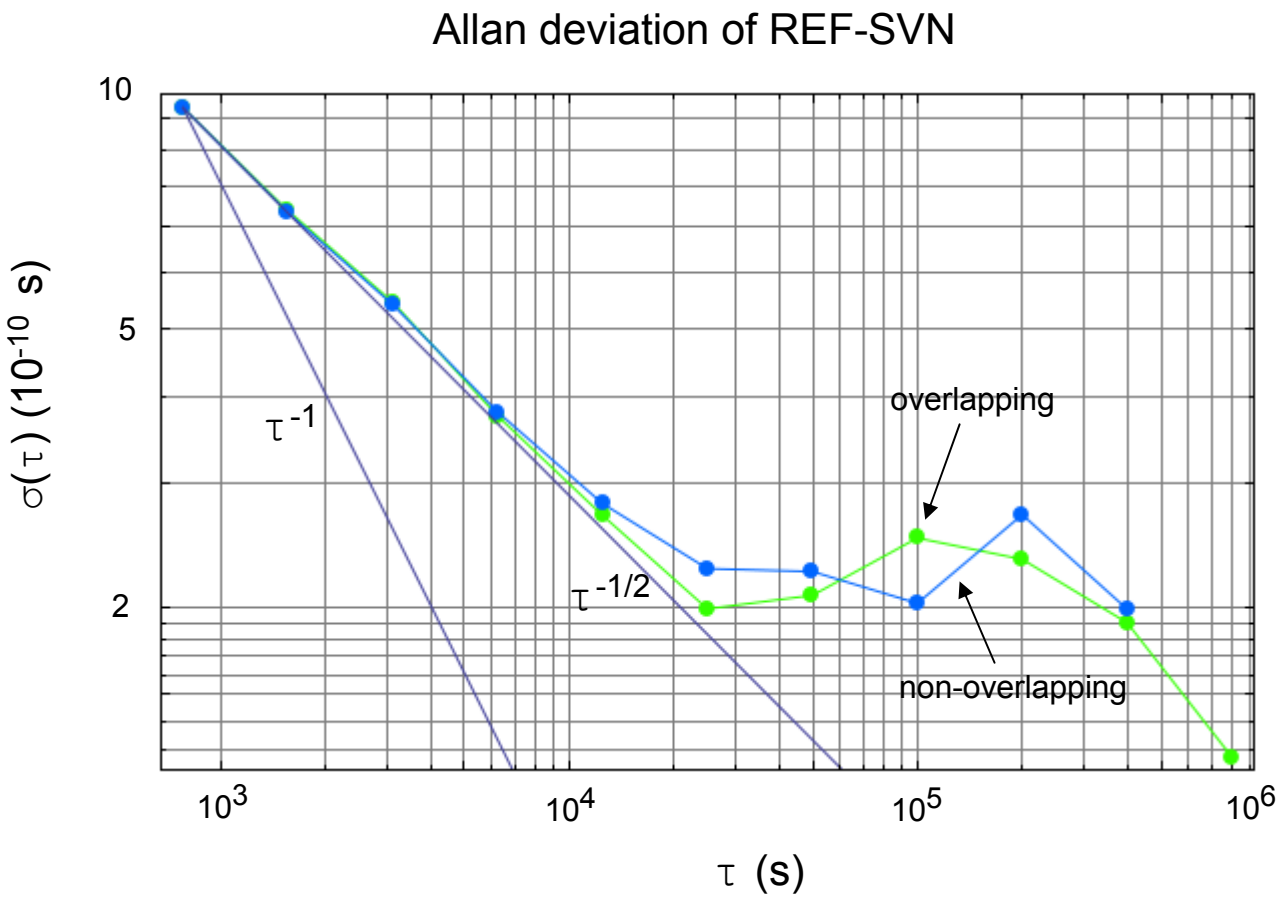
Checking for biases



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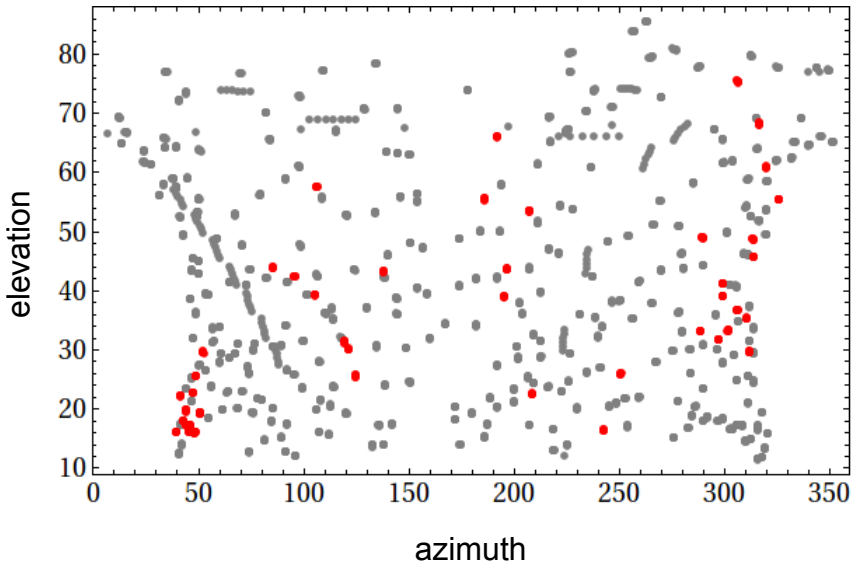
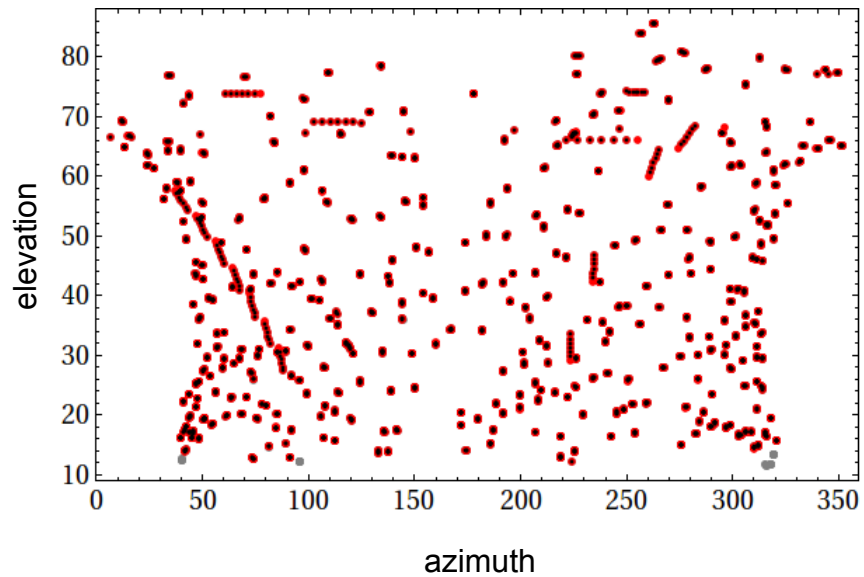
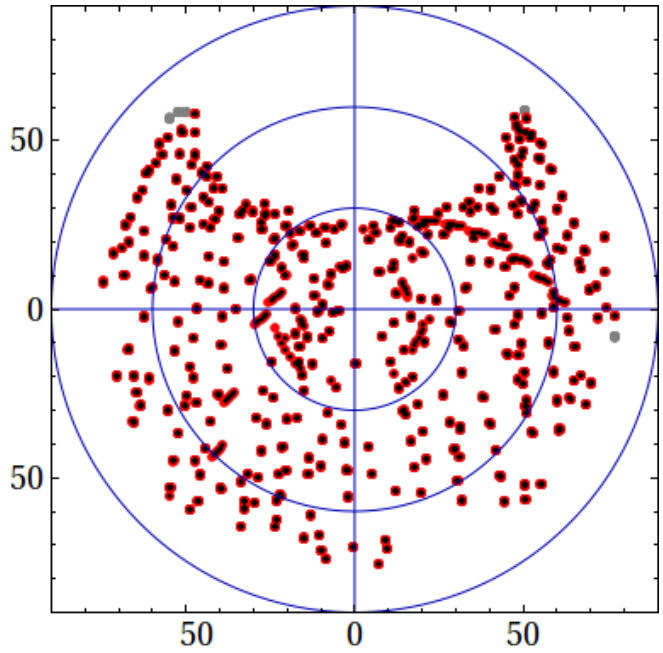
More bias checks

Travelling receiver: Schedule (●) and non-schedule (●) tracks





travelling
host
matched



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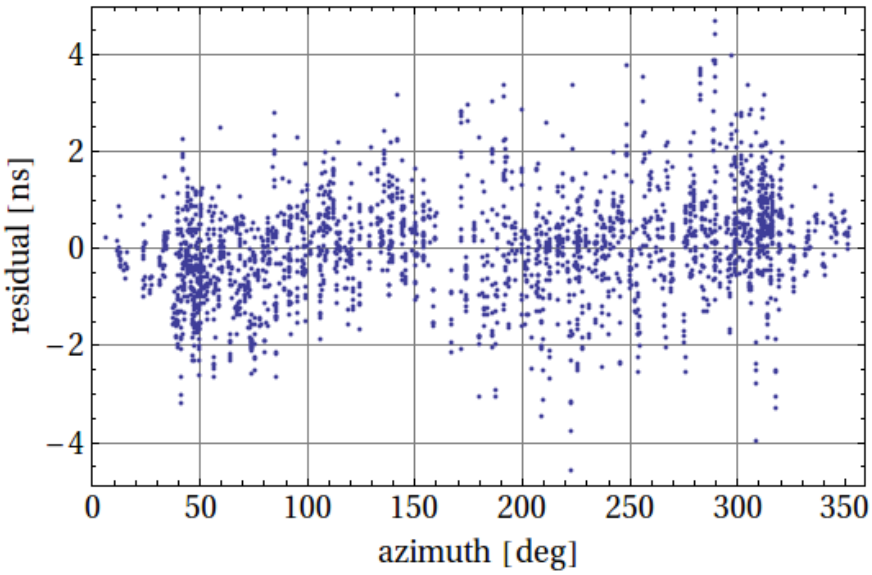
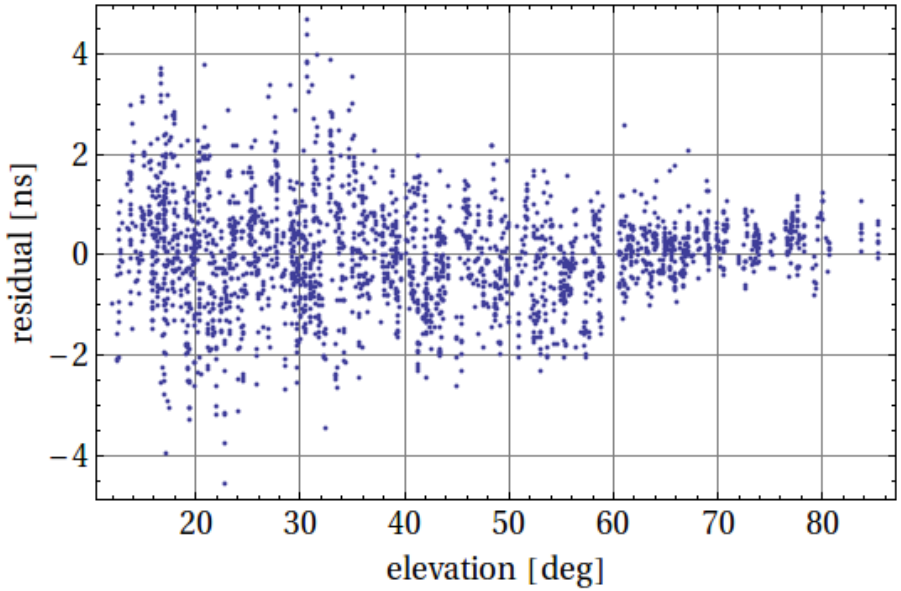
Even more bias checks

Plot residuals of the fit to (REF-SVN) as a function of azimuth and elevation





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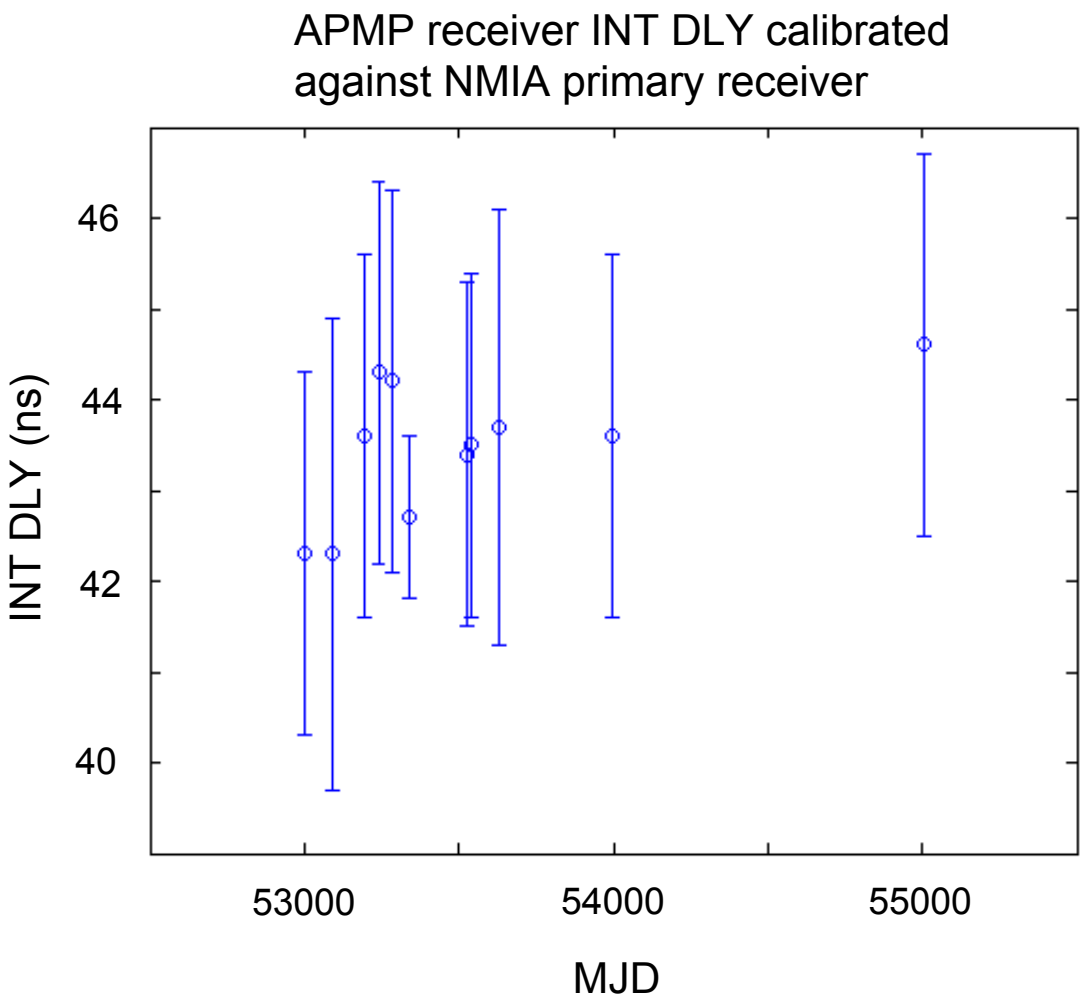
An aside: long term stability



INT DLY (comparison, ns)		
MJD	Value	RMS
53000	42.3	2.0
53092	42.3	2.6
53195	43.6	2.0
53240	44.3	2.1
53284	44.2	2.1
53342	42.7	0.9
53524	43.4	1.9
53539	43.5	1.9
53630	43.7	2.4
53995	43.6	2.0
55006	44.6	2.1

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An exercise

Calibrate the MSL host receiver using data collected during APMP 2012

Data will be available at

ftp://time.nmi.gov.au/APMP2012/exercise

Results will be posted later on the ftp server

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Resources

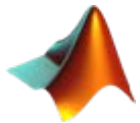
This presentation ...

PLUS

perl script for reading and comparing CCTF data

Mathematica notebook for analysis of CCTF data

(with thanks to Bruce Warrington, NMIA)



MATLAB files for analysis of CCTF data

(with thanks to Magnus Hsu, NMIA)

All available from

ftp://time.nmi.gov.au/APMP2012/resources

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