FIG WORKING WEEK 2017
Helsinki Finland
29 May - 2 June 2017

Triple Frequency multi-GNSS Cycle Slip Detection using Ionospheric Residuals

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Cycle Slips

- Limiting factor when using carrier phase GNSS
- Caused by physical and electromagnetic influences
- Several techniques to detect and correct for cycle slips, using triple frequency, comparing the carrier with the code, use of wide lane etc
- Noise disadvantages when using the code, especially Multipath, and usually not accurate to 1 cycle
- Detect and/or correct?

RINEX file 1991

```
     1              OBSERVATION DATA                        RINEX VERSION / TYPE
W2RINEXO V1.1       IESSG               16-DEC-91 13:50     PGM / RUN BY / DATE
Central Greece GPS Project 1991                             COMMENT
sta 60                                                      MARKER NAME
Bingley             Group 3                                 OBSERVER / AGENCY
   175              WM102                                   REC # / TYPE / VERS
   136              WM102                                   ANT # / TYPE
  4663890.7450  1879921.4090  3911786.2160                  APPROX POSITION XYZ
        1.3240         .0000         .0000                  ANTENNA: DELTA H/E/N
     1     1                                                WAVELENGTH FACT L1/2
     4    C1    L1    P2    L2                              # / TYPES OF OBSERV
    30                                                      INTERVAL
  1991    10     5    15    29      .000000                 TIME OF FIRST OBS

 91 10  5 19 38   .0000000  0  4 24  6 18 19
  22399677.144   -9577162.533 6  22399665.498   -7462709.290 6
  23993822.484   -1510155.432 5  23993824.368   -1176750.659 5
  21212943.503  -10651435.258 7  21212931.337   -8299771.986 6
  20041050.461  -20532352.558 6  20041035.264  -15999270.670 6
```

RINEX 3.02 file the day before yesterday

- > 2017 5 30 6 26 21.0000000 0 48
- G 7 23316589.867 122529532.848 4163.887 43.750 23316594.535 95477595.074 3244.586 27.000 23316594.277 95477579.078 3244.586 39.250
- R17 21167052.508 113269184.346 -2056.195 48.000 21167051.617 113269152.375 -2056.195 47.000 21167057.172 88098236.273 -1599.262 45.750 21167057.117 88098244.270 -1599.262 44.000
- G26 24959732.828 131164335.623 1338.172 36.500 24959742.945 102205988.063 1042.730 18.500 24959742.781 102205975.111 1042.730 37.250 24959742.840 97947394.689 999.285 42.500
- G17 24251259.719 127441237.030 -1890.508 40.750 24251266.105 99304858.404 -1473.121 22.500 24251265.652 99304850.448 -1473.121 38.000
- R 3 22583525.586 120891401.389 2442.586 45.000 22583524.230 120891363.405 2442.586 43.750 22583528.730 94026636.306 1899.789 42.250 22583529.352 94026623.298 1899.789 40.750
- R12 20421754.023 109089387.066 2206.559 50.250 20421752.922 109089369.083 2206.559 48.750

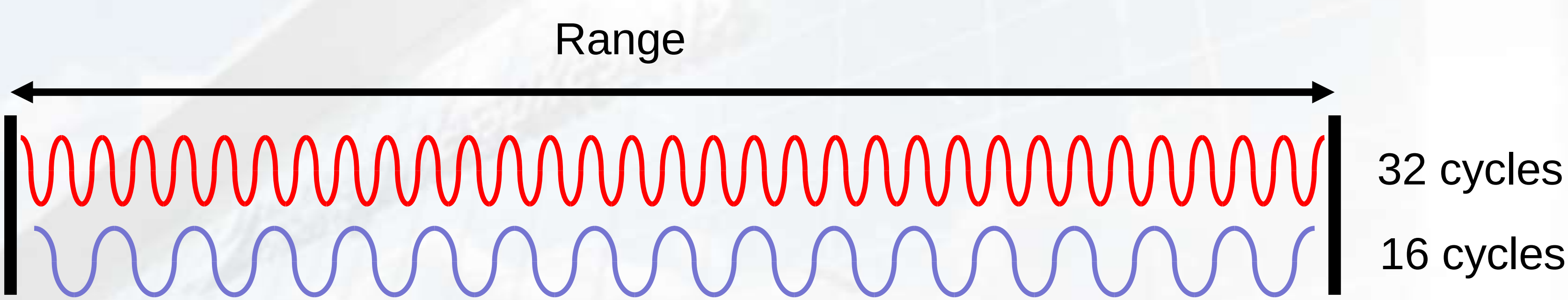
C 4 38687612.000 201456684.065 286.230 37.250 38687601.512 163700007.856 232.586 42.000 38687606.492 155779053.051 221.332 41.000

19419

- R13 22997427.961 122804989.371 4634.602 36.750 22997426.969 122804984.355 4634.602 35.500 22997434.563 95514993.190 3604.691 32.750 22997435.156 95515000.145 3604.691 31.500
- G 1 21789513.586 114504661.144 -2804.301 45.250 21789522.398 89224445.906 -2185.168 35.750 21789521.895 89224412.923 -2185.168 48.000 21789522.191 85506746.217 -2094.121 51.500
- G 3 20633876.055 108431772.107 59.883 52.250 20633882.887 84492338.871 46.660 43.750 20633882.766 84492310.873 46.660 50.750 20633885.246 80971808.324 44.719 55.500
- G 6 23234863.938 122100057.020 3189.160 40.000 23234872.039 95142930.252 2485.059 27.000 23234872.711 95142906.257 2485.059 42.000 23234875.438 91178652.089 2381.516 47.500
- R11 21744827.859 116197796.867 -1500.711 48.250 21744826.676 116197768.867 -1500.711 46.500 21744831.164 90376061.214 -1167.219 43.750 21744831.375 90376075.241 -1167.219 42.250
- G23 20241881.945 106371861.984 -127.203 53.500 20241883.859 82887184.943 -99.121 42.000
- R18 21994840.289 117409956.013 1389.867 46.500 21994840.129 117409940.027 1389.867 46.000 21994846.156 91318854.217 1081.008 42.750 21994846.195 91318849.218 1081.008 41.500
- G31 24781269.195 130226485.680 -2867.555 38.000 24781274.641 101475202.353 -2234.457 18.500 24781273.121 101475159.351 -2234.457 34.500
- G22 21623663.234 113633150.460 -1562.016 49.500 21623665.691 88545318.054 -1217.156 38.000
- R 2 20269924.000 108164229.651 683.734 53.500 20269923.406 108164198.652 683.734 51.500 20269928.441 84127727.248 531.793 47.250 20269928.637 84127720.226 531.793 45.500
- C10 40594653.906 211387030.265 1831.953 34.250 40594645.527 171769245.081 1488.613 35.250 40594654.777 163457827.287 1416.582 34.500
- C 9 36680974.266 191007460.201 257.262 47.500 36680962.008 155209167.698 209.047 47.750 36680970.211 147699050.176 198.930 46.750
- C 7 38719157.180 201620868.809 2096.527 40.000 38719143.289 163833457.173 1703.602 41.000 38719152.082 155905984.115 1621.168 40.500
- C 6 35999168.523 187457117.018 160.840 49.250 35999156.406 152324219.062 130.695 49.000 35999163.238 144953690.305 124.371 47.250
- C 8 39556670.813 205981941.203 -1576.121 38.750 39556658.520 167377166.232 -1280.727 40.500 39556666.512 159278258.942 -1218.758 40.250
- C14 22030262.898 114717395.965 1173.348 51.000 22030250.840 93217244.232 953.441 52.000 22030258.738 88706739.267 907.309 49.500
- C11 25358731.461 132049546.026 -2528.656 38.500 25358722.074 107301026.722 -2054.742 41.750 25358731.168 102109042.905 -1955.316 41.500
- C13 37631902.188 195959177.015 -1445.156 45.500 37631894.559 159232864.549 -1174.309 45.000 37631903.094 151528035.400 -1117.488 43.000
- C 5 39400451.719 205168440.474 226.367 35.750 39400443.891 166716137.529 183.941 39.500 39400448.496 158649233.995 175.043 38.500
- C 4 38687612.000 201456684.065 286.230 37.250 38687601.512 163700007.856 232.586 42.000 38687606.492 155779053.051 221.332 41.000
- C 3 37069336.992 193029757.877 263.996 42.000 37069326.949 156852428.385 214.520 47.250 37069331.320 149262817.980 204.137 45.750
- C 2 37553597.438 195551438.510 242.105 38.000 37553588.672 158901521.981 196.730 43.750 37553592.012 151212747.325 187.211 42.500
- C 1 37426214.039 194888095.007 306.586 41.750 37426200.852 158362468.046 249.125 45.000 37426205.637 150699795.085 237.070 45.750
- E 5 28377901.313 149126849.214 -1473.316 37.500 28377909.172 111360971.698 -1100.203 33.750 28377906.398 114266032.508 -1128.906 36.000 28377907.836 112813494.711 -1114.555 37.500
- E22 26841144.836 141051097.866 -2585.164 36.000 26841152.262 105330367.687 -1930.480 35.750 26841150.719 108078106.525 -1980.840 38.500 26841151.340 106704238.199 -1955.660 40.000
- E26 25758124.188 135359861.278 2071.516 39.500 25758133.328 101080450.556 1546.910 39.250 25758129.910 103717311.714 1587.266 39.000 25758131.207 102398879.250 1567.090 41.750
- E 7 27270755.375 143308780.164 1947.055 42.500 27270763.082 107016340.289 1453.969 40.750 27270759.438 109808053.611 1491.898 40.750 27270761.148 108412194.555 1472.934 44.000
- E 2 25386933.250 133409315.189 2610.477 46.750 25386938.879 99623830.226 1949.383 46.750 25386935.887 102222613.945 2000.234 46.500 25386937.230 100923218.187 1974.809 49.250
- E24 27983633.797 147054998.975 -1688.695 39.500 27983651.707 109813872.067 -1261.039 39.000 27983648.430 112678570.239 -1293.934 38.000 27983648.656 111246130.764 -1277.488 41.000
- E 8 22056401.414 115907202.445 884.379 53.000 22056406.223 86554106.400 660.414 50.500 22056403.238 88812027.718 677.641 50.250 22056404.340 87683063.666 669.027 52.500
- E18 20957233.516 110131001.428 1695.410 42.250 20957245.379 82240613.184 1266.055 42.000 20957242.926 84386022.521 1299.082 41.750 20957243.512 83313319.460 1282.566 44.500
- S28 37798443.438 198632140.704 284.004 43.250 37798428.973 148329134.637 212.082 46.250
- S37 37602516.328 197602493.883 278.828 40.750

Ionospheric Residual

- Carrier phase measure the change in ranges.
- Possible to convert into an equivalent phase measurement on another frequency
- However, systematic errors exist due to the ionosphere, which change slowly over time
- By calculating this systematic error, it is possible to detect any jumps and hence cycle slips
- RE-visit my PhD work from 1997



Ionospheric Residual

$$c = f_{L1} . \lambda_{L1} = f_{L2} . \lambda_{L2} = f_{L5} . \lambda_{L5}$$

But only in a vacuum

$$IR_a = \phi_a - \phi_b . \left(\frac{f_a}{f_b}\right) + \varepsilon$$

ε = error values due to the ionosphere, troposphere, receiver noise as well as the integer ambiguity

$$\delta IR = \left(\phi_a - \phi_b . (\frac{f_a}{f_b})\right)_{(i)} - \left(\phi_a - \phi_b . (\frac{f_a}{f_b})\right)_{(i-1)}$$

Refinement Integer Values for ±5 cycles

		RML1										
		-5	-4	-3	-2	-1	0	1	2	3	4	5
RML5	-5	1.696	2.696	3.696	4.696	5.696	6.696	7.696	8.696	9.696	10.696	11.696
	-4	0.357	1.357	2.357	3.357	4.357	5.357	6.357	7.357	8.357	9.357	10.357
	-3	-0.983	0.017	1.017	2.017	3.017	4.017	5.017	6.017	7.017	8.017	9.017
	-2	-2.322	-1.322	-0.322	0.678	1.678	2.678	3.678	4.678	5.678	6.678	7.678
	-1	-3.661	-2.661	-1.661	-0.661	0.339	1.339	2.339	3.339	4.339	5.339	6.339
	0	-5.000	-4.000	-3.000	-2.000	-1.000	0.000	1.000	2.000	3.000	4.000	5.000
	1	-6.339	-5.339	-4.339	-3.339	-2.339	-1.339	-0.339	0.661	1.661	2.661	3.661
	2	-7.678	-6.678	-5.678	-4.678	-3.678	-2.678	-1.678	-0.678	0.322	1.322	2.322
	3	-9.017	-8.017	-7.017	-6.017	-5.017	-4.017	-3.017	-2.017	-1.017	-0.017	0.983
	4	-10.357	-9.357	-8.357	-7.357	-6.357	-5.357	-4.357	-3.357	-2.357	-1.357	-0.357
	5	-11.696	-10.696	-9.696	-8.696	-7.696	-6.696	-5.696	-4.696	-3.696	-2.696	-1.696

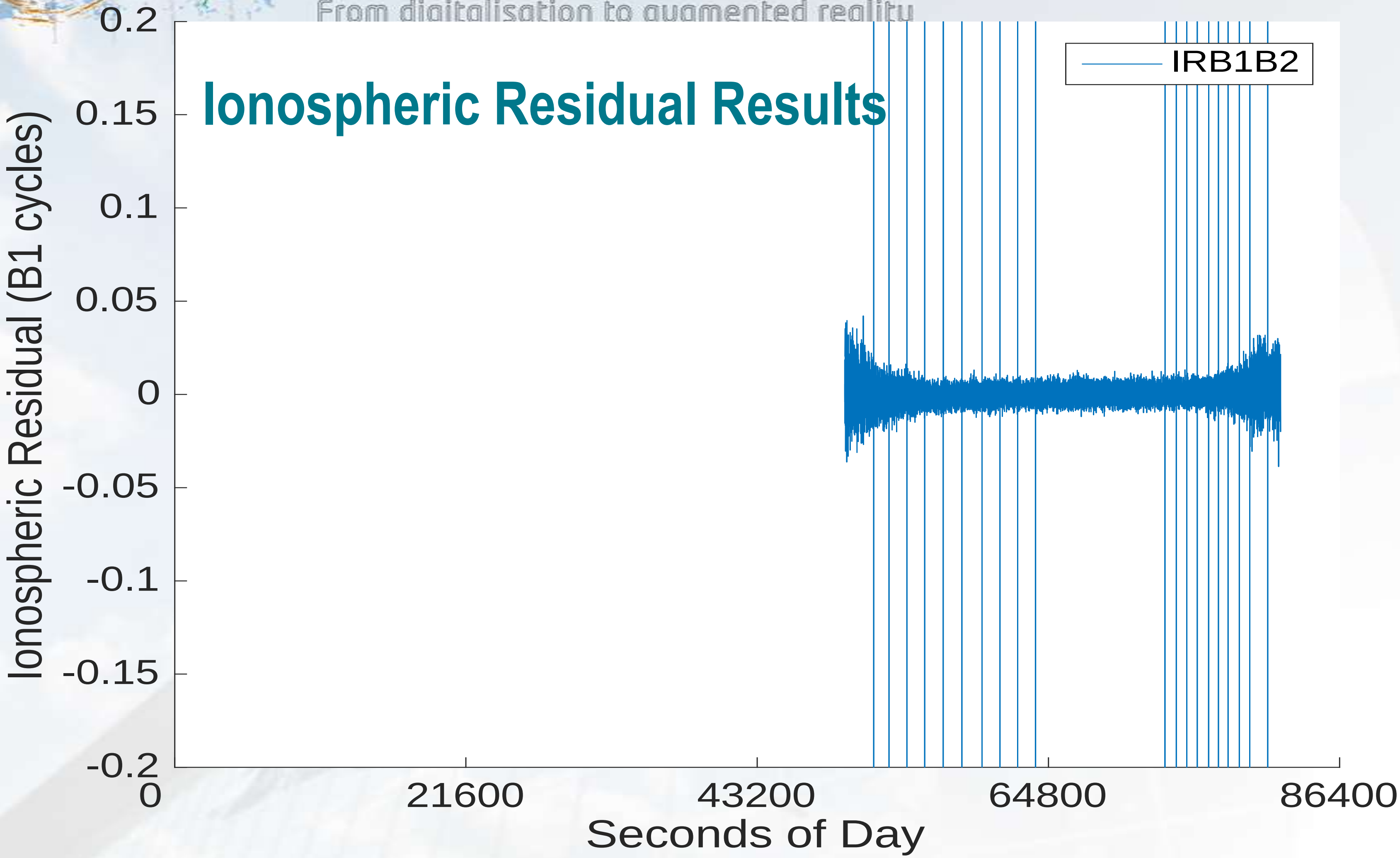
Ionospheric Residual - However

- As the search becomes bigger, then the differences between possible solutions becomes smaller, and within the noise of the carrier
- Also, the solutions are no longer unique eg ±1000 cycles

		± 10 cycles			± 100 cycles			± 1000 cycles		
	Ionospheric Residual Combination	% Unique Solutions	Number of "zero" solutions	Number of repeating combinations	% Unique Solutions	Number of "zero" solutions	Number of repeating combinations	% Unique Solutions	Number of "zero" solutions	Number of repeating combinations
GPS	L1L2	100	1	0	75.23	3	2	1.9	11	22
	L1L5	100	1	0	89.54	9	1	3.26	13	12
	L2L5	100	1	0	9.8	1	8	0.5	83	83
BeiDou	B1B2	100	1	0	100	1	0	58.43	3	2
	B1B3	100	1	0	100	1	0	57.94	3	2
	B2B3	100	1	0	46.85	3	3	0.83	33	34

L1	L5	IR L1L5
-924	-690	0
-770	-575	0
-616	-460	0
-462	-345	0
-308	-230	0
-154	-115	0
0	0	0
154	115	0
308	230	0
462	345	0
616	460	0
770	575	0
924	690	0

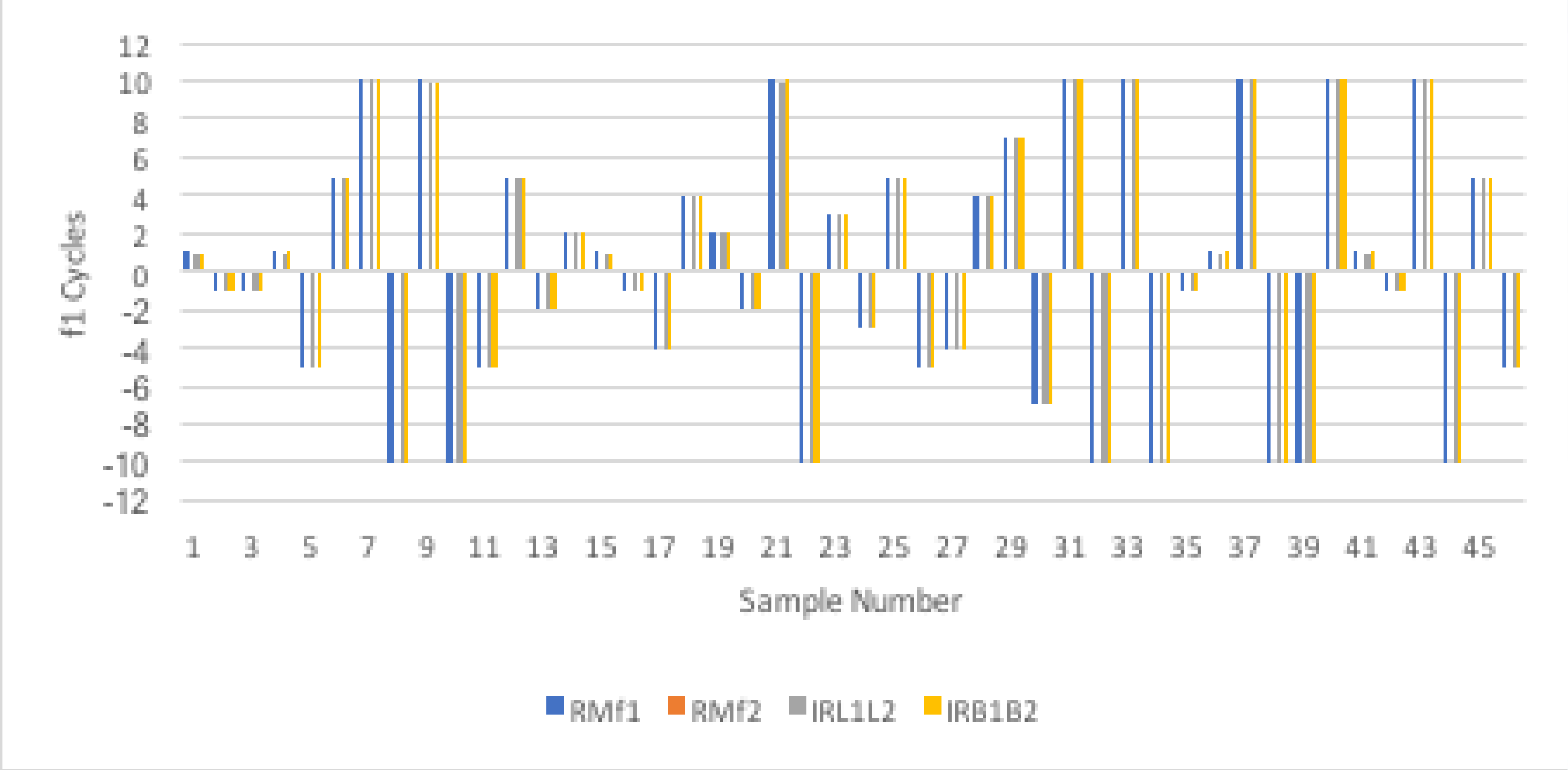
Ionospheric Residual Results



Ionospheric Residual Results

		Elevation Cut Off Angle (°)										
		0	10	15	20	25	30	35	40	45	50	55
GPS SV25	L1L2CW	0.0107	0.0065	0.0054	0.0048	0.0044	0.0042	0.0041	0.0041	0.0041	0.0042	0.0042
	L1L2CX	0.0063	0.0050	0.0045	0.0043	0.0042	0.0041	0.0040	0.0041	0.0041	0.0041	0.0041
	L1L5CX	0.0057	0.0046	0.0043	0.0042	0.0041	0.0041	0.0041	0.0042	0.0042	0.0043	0.0043
	L2L5WX	0.0082	0.0054	0.0048	0.0045	0.0044	0.0043	0.0043	0.0044	0.0044	0.0045	0.0045
	L2L5XX	0.0050	0.0044	0.0043	0.0042	0.0042	0.0043	0.0043	0.0043	0.0044	0.0045	0.0045
No Samples		*28,210*	*24,660*	*22,740*	*20,820*	*18,960*	*17,100*	*15,240*	*13,440*	*11,820*	*10,200*	*8,400*
BeiDou SV12	B1B2	0.0054	0.0045	0.0040	0.0038	0.0036	0.0036	0.0036	0.0036	0.0035	0.0036	0.0036
	B1B3	0.0052	0.0045	0.0042	0.0042	0.0041	0.0041	0.0041	0.0041	0.0041	0.0041	0.0042
	B2B3	0.0047	0.0042	0.0040	0.0039	0.0039	0.0039	0.0039	0.0039	0.0040	0.0040	0.0041
No Samples		*32,326*	*29,220*	*26,760*	*24,660*	*22,500*	*20,400*	*18,300*	*15,960*	*13,860*	*11,760*	*9,600*
Galileo SV18	E1E5	0.0046	0.0038	0.0037	0.0036	0.0036	0.0035	0.0034	0.0034	0.0034	0.0033	0.0033
	E1E5a	0.0048	0.0039	0.0038	0.0037	0.0036	0.0035	0.0035	0.0034	0.0034	0.0033	0.0033
	E1E5b	0.0047	0.0038	0.0037	0.0036	0.0035	0.0035	0.0034	0.0033	0.0033	0.0033	0.0032
	E5aE5	0.0036	0.0035	0.0035	0.0034	0.0034	0.0034	0.0034	0.0033	0.0033	0.0033	0.0033
	E5aE5b	0.0039	0.0035	0.0035	0.0034	0.0034	0.0034	0.0033	0.0033	0.0033	0.0033	0.0033
	E5bE5	0.0037	0.0036	0.0035	0.0035	0.0035	0.0034	0.0034	0.0034	0.0034	0.0033	0.0033
No Samples		*33,650*	*30,180*	*28,380*	*26,460*	*24,540*	*22,620*	*20,700*	*18,600*	*16,740*	*14,580*	*12,720*

Simulated Cycle Slips



Conclusions

- Can be applied to all carrier phase GNSS frequencies pairs
- A few problems with this approach include the the number of non-unique solutions and similar solutions as the search range expands
- Similarly with the number of solutions resulting in a value of zero
- However, this technique works well at, for example, ±10 cycles
- So, detect a cycle slip, and use another technique to correct to this value first

Triple Frequency multi-GNSS Cycle Slip Detection using Ionospheric Residuals

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