An Experimental Analysis of Code/Carrier Tracking Performance In The Trimble SK-8 GPS Receiver

Pascal Stang
AA272D, Stanford University, CA 94305

1. Introduction

Every day, small, cheap, mass-produced GPS receivers reach new markets because of advances in performance, power consumption, size, weight, and a host of other factors. In the research world, these receiver have benefited a great many experiments producing time, position, and velocity outputs at extremely low cost. While many of the limitations of small commercial GPS receivers are being overcome, some continue to stand. Of specific interest to aeronautics and astronautics researchers are the limitations on altitude, speed, and dynamics. Whether imposed by governmental regulation or by the receiver technology itself, these limits often make it impossible to use the ubiquitous commercial GPS receiver in Aero/Astro research involving high-performance aircraft or satellites. This paper documents the testing of one such receiver, the Trimble SK-8, to determine where such limits actually lie and whether they can be bypassed.

2. The Trimble SK-8 GPS Receiver

The Trimble SK-8 GPS Receiver is a typical inexpensive receiver mass-produced by Trimble Navigation LTD in Sunnyvale, California. The receiver is has double down-conversion ASIC RF section, a integrated 8-channel DSP and Motorola 68000 processor, 128K of SRAM and 2MB of program ROM. This unit is sold for about $80 each in quantities of 1000. It comes in a range of sizes from 1.35”x2.25”x0.5” to 3.25”x5”x.75” depending on application and interface features.

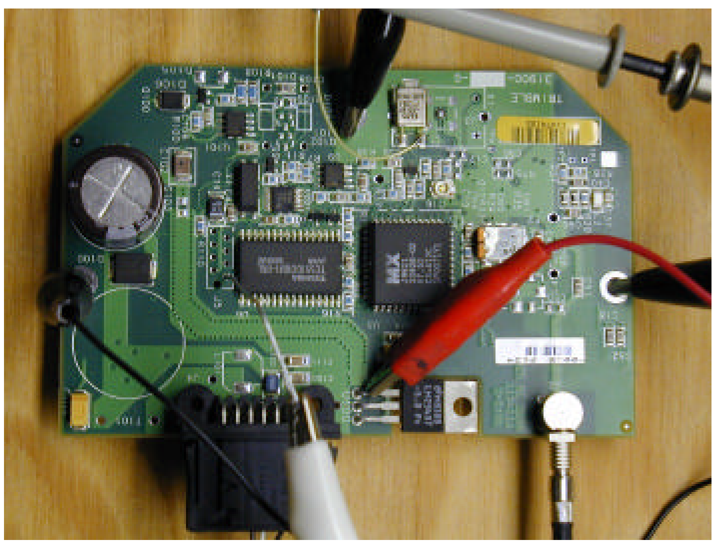


Figure 1 - Trimble SK-8 GPS Receiver (Automotive version)

The Trimble documentation for this receiver states that the altitude and dynamic limits are:

- Altitude: -1,000m to +18,000m
- Velocity: 515m/sec
- Acceleration: 4g (39.2m/sec^2)
- Jerk: 20m/sec^3

The documentation also mentions that the altitude limit and the velocity limit may be exceeded, but due to governmental regulation, only one may be over limit at a time. This suggests that these limits are, to some degree, artificially induced in the unit’s firmware. While the altitude limit is solely a function of the position solution software, the speed and dynamic limits may be either a function of software, or due, in part, to limits on the receiver's code and carrier phase tracking loops. The source of the limits will determine whether this receiver can effectively be used outside it's published envelope. If the receiver can indeed track satellites while experiencing dynamics greater than those listed above, then any limits in the position solution code can be circumvented by using raw output from the receiver and solving for position externally.

3. Experimental Setup

Testing the limits of the receiver as a whole, including the position solution code, requires GPS signal simulator hardware that can support the coordinated simulation of at least 4 satellites. However, since we are interested primarily in tracking performance, a characterization of code and carrier phase tracking can be done with a significantly simpler single-channel simulator. This is what has been employed below (*figure 2 and 3*).

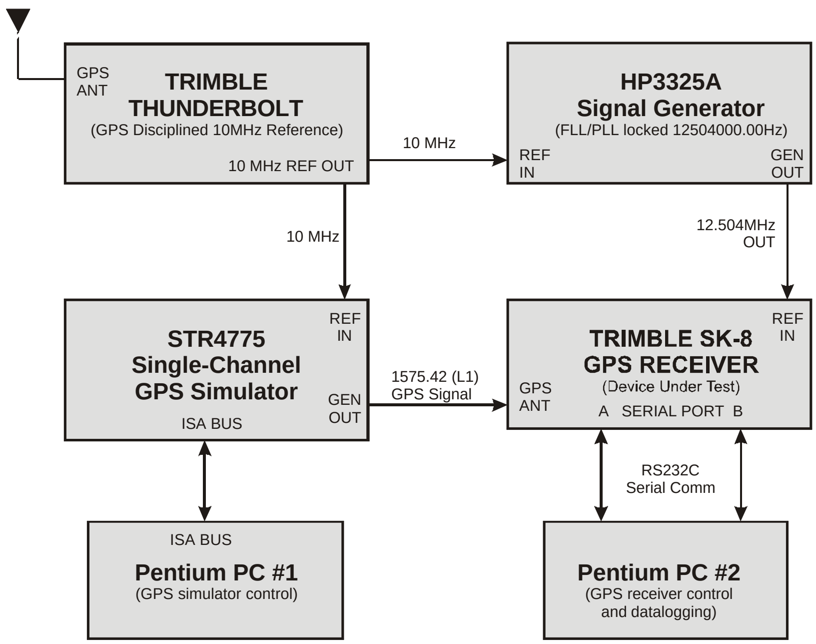


Figure 2 - Testing Setup Component/Signal Diagram

The experimental setup is comprised of six main components: a Trimble Thunderbolt GPS-disciplined clock, an HP3325A function generator, a GSS STR4775 single-channel GPS simulator, one Trimble SK-8 under test, and two Pentium-class PCs.

The Thunderbolt clock provides a steady 10MHz time reference which is used to keep the GPS simulator and Trimble receiver synchronized the same time reference. This is important since any offset in time reference between the simulator and the receiver will manifest as unwanted Doppler and code phase slewing. Under ordinary circumstances, the GPS receiver would use four or more satellite signals and a position/time solution to keep its

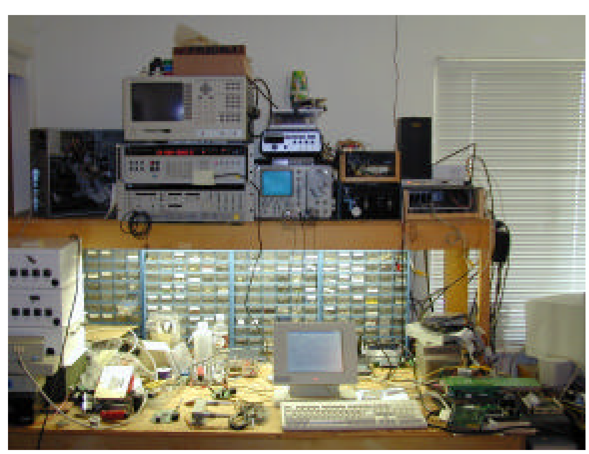


Figure 3 – Experimental Setup

own internal clock precisely synchronized to GPS time. This is impossible here since only one satellite signal will be available. Instead, the receiver's timing reference, a 12.504MHz crystal, is replaced with a 0.5Vp-p 12.504MHz sine wave from the HP signal generator. To maintain the necessary common time reference, both the signal generator and the GPS simulator are PLL-locked to the Thunderbolt's output. Two PCs provide control support for the experiment. One PC operates as a host and interface to the STR4775 simulator card while the other PC handles configuration of the GPS receiver, data logging, and post-processing. (*see figure 3*)

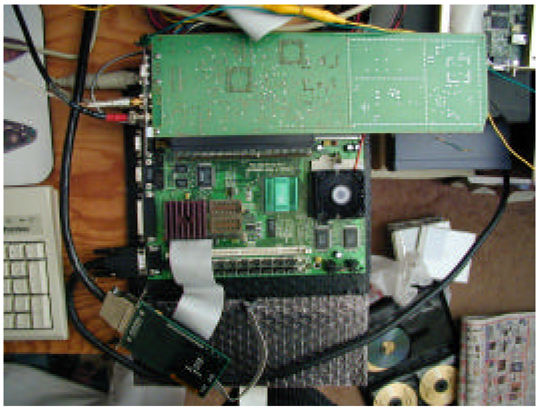


Figure 4 – Pentium PC #1

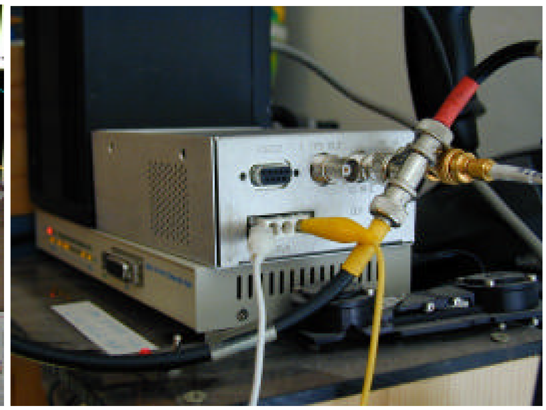


Figure 5 - Trimble Thunderbolt Reference

4. Results

The results and data from the experimental setup can be expressed as a set of simulator profiles each with a corresponding data-logged code and carrier tracking response from the Trimble GPS receiver. A simulator profile is comprised of four parameters which exactly define an acceleration, velocity, and range path for the simulated GPS signal. The path generation sequence is shown in figure 6 where A is the maximum jerk, B is the jerk period calculated as (jerk/maximum acceleration), C is the constant acceleration period, D is the constant velocity period, and E is the maximum acceleration.

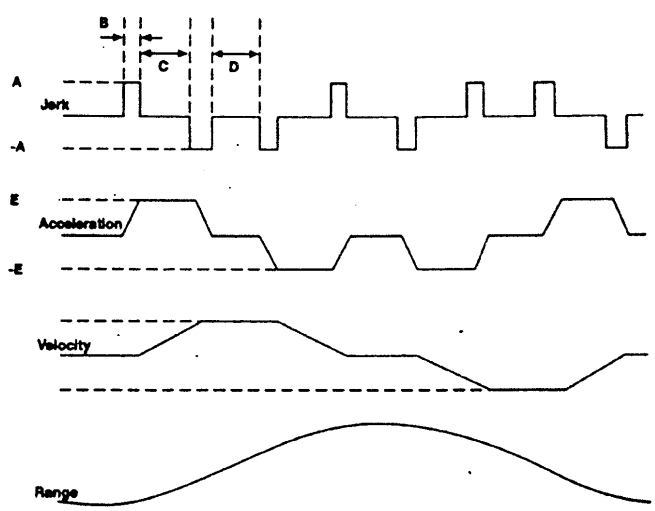


Figure 6 - Simulator Profile Generation

4.1. Velocity Limit Testing

The first five simulator profiles were used to test the receiver's code tracking and Doppler velocity limits. It should be noted that the velocity limits characterized by these profiles are *not* user velocity relative to ECEF or ENU but rather velocity relative to the orbiting GPS satellite in question. However, the maximum code/carrier tracking velocity does directly impact the maximum user velocity, where the specific relationship between these two velocities can be found given a satellite geometry.

Profile 1 was run to establish compliance to the published limits of the receiver and indeed resulted in 100% reliable output. Profile 2 far exceeded the sum of the user velocity limit (515m/s) and a typical satellite velocity (1200m/s relative to user) yet did not cause the receiver's tracking to falter. Profiles 3 and 4 were explicitly designed to push the receiver into failure and succeeded in railing the Doppler output at -15013m/s (78818Hz). Interestingly, the plots for profiles 3 and 4 show that while the Doppler output was railed, the code phase continued to be accurate in excess of 15km/s. While that may indicate that the Doppler error was simply a numeric limitation, for the purposes of the user it is considered a failure. Finally, profile 5 was designed to stress the receiver's acceleration response and loop tracking while nearing velocity limits. Output reliability was 100% for all profiles.

Profile* number	Jerk (m/s^3)	Maximum Acceleration (m/s^2)	Period of Constant Acceleration (sec)	Period of Constant Velocity (sec)	Max Velocity (m/s)	Output (%)**
1	20	39.2	13	1	+/-587	100
2	2	100	40	10	+/-9000	100
3	4	100	150	1	-15013	100
4	4	100	800	1	-15013	100
5	4	200	20	10	+/-14000	100

*NOTE: Plots of profiles and GPS output may be found in Appendix A

** Output quality is defined as the accuracy and availability of output at 1Hz

4.2. Acceleration Limit Testing

Profiles 6 though 12 were aimed at testing the receiver's acceleration response which is effectively a test of tracking loop performance and bandwidth***. The receiver's specified limit for acceleration is $39.2 m/s^2$ (4Gs) yet previous tests already established higher levels of performance. Profiles 6 and 7 qualified the receiver out to $225 m/s^2$ (23G) with 100% reliability. Profiles 8 to 12 exhibited reporting dropouts during high accelerations, yet the receiver was still able to track in during periods of lower acceleration.

Profile* Number	Jerk (m/s^3)	Maximum Acceleration (m/s^2)	Period of Constant Acceleration (sec)	Period of Constant Velocity (sec)	Max Velocity (m/s)	Output (%)**
6	10	200	1	1	+/-4200	100
7	20	225	1	1	+/-2757	100
8	20	250	1	1	+/-3375	92.2
9	20	300	1	1	+/-4801	81.5
10	20	400	1	1	+/-8400	66
11	20	400	1	1	+/-8400	67.7
12	40	400	1	1	+/-4400	69

*NOTE: Plots of profiles and GPS output may be found in Appendix A

** Output quality is defined as the accuracy and availability of output at 1Hz

5. Conculsion

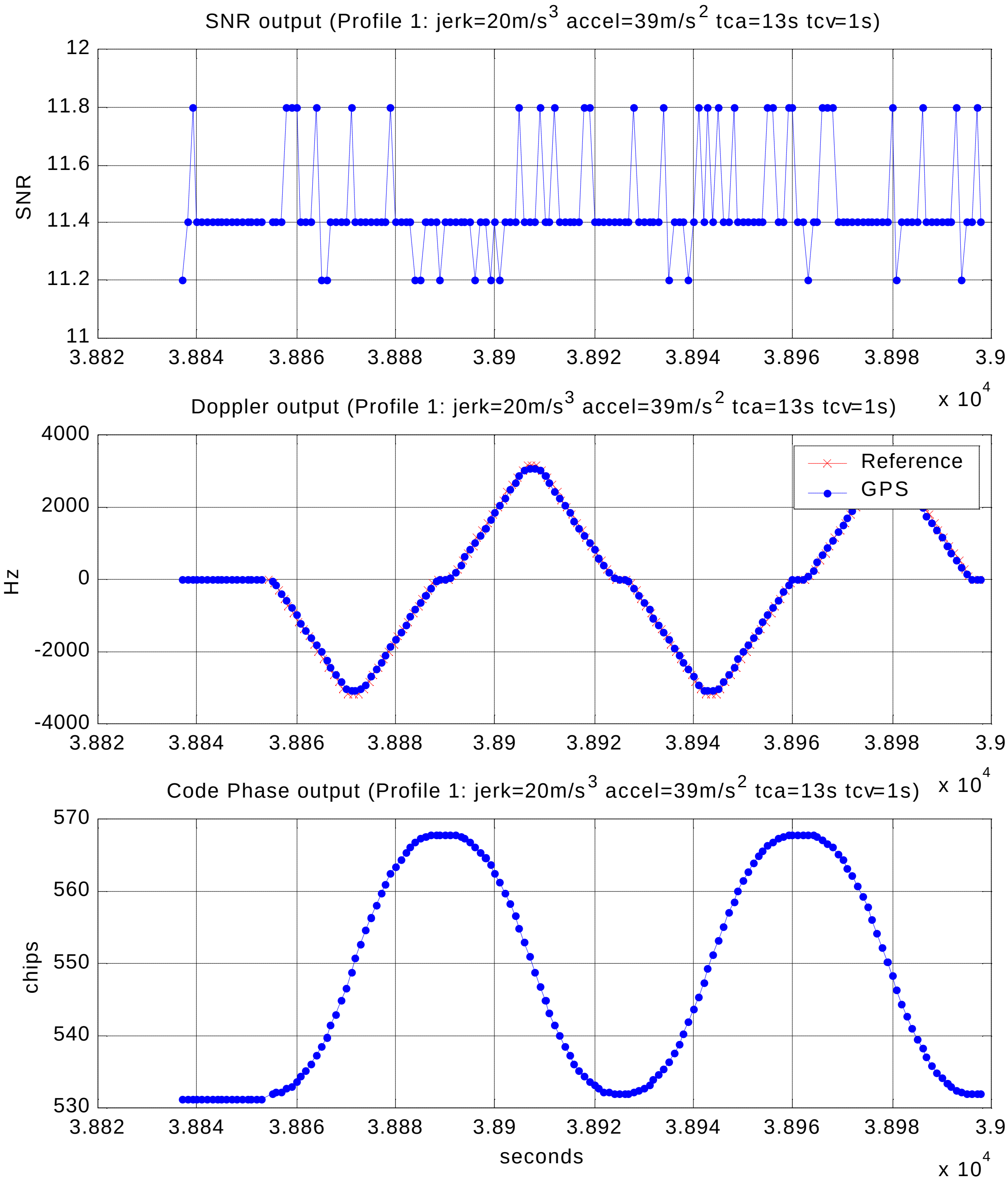
Returning to our original question regarding the location of velocity and dynamics limits in the Trimble SK-8 receiver, the experiments presented here strongly suggest that the limits are being imposed at the position solution level. Therefore, in applications where position solutions can be calculated externally, this receiver may be usable for velocities extending into the range of several kilometers per second and accelerations as high as tens of Gs.

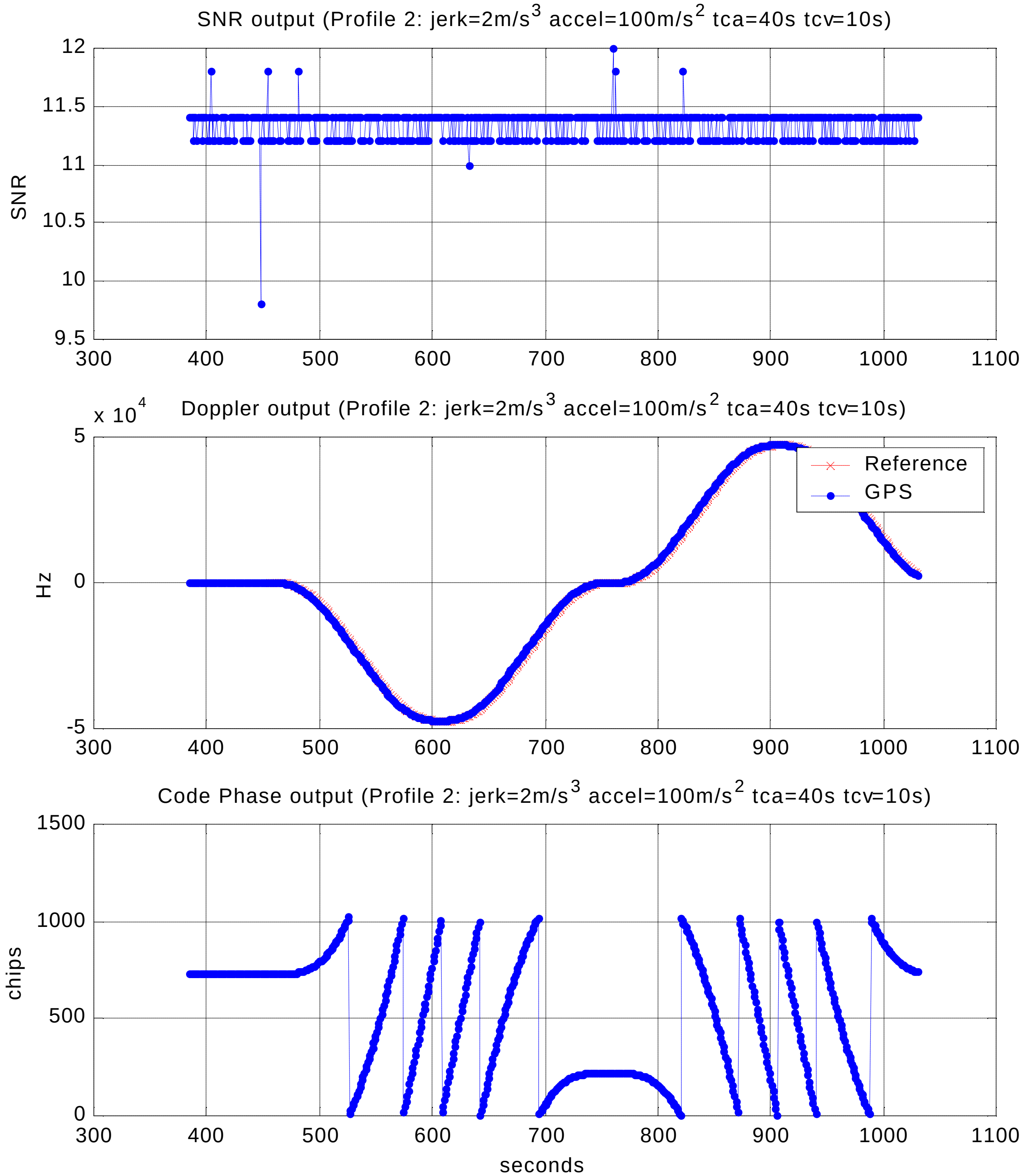
Further single-channel simulations should focus on testing acquisition, while a full-constellation high-velocity/dynamics simulation could prove interesting in establishing cheap commercial GPS receivers as a potential choice for research vehicles where cost or quick turn-around is a driving design parameter.

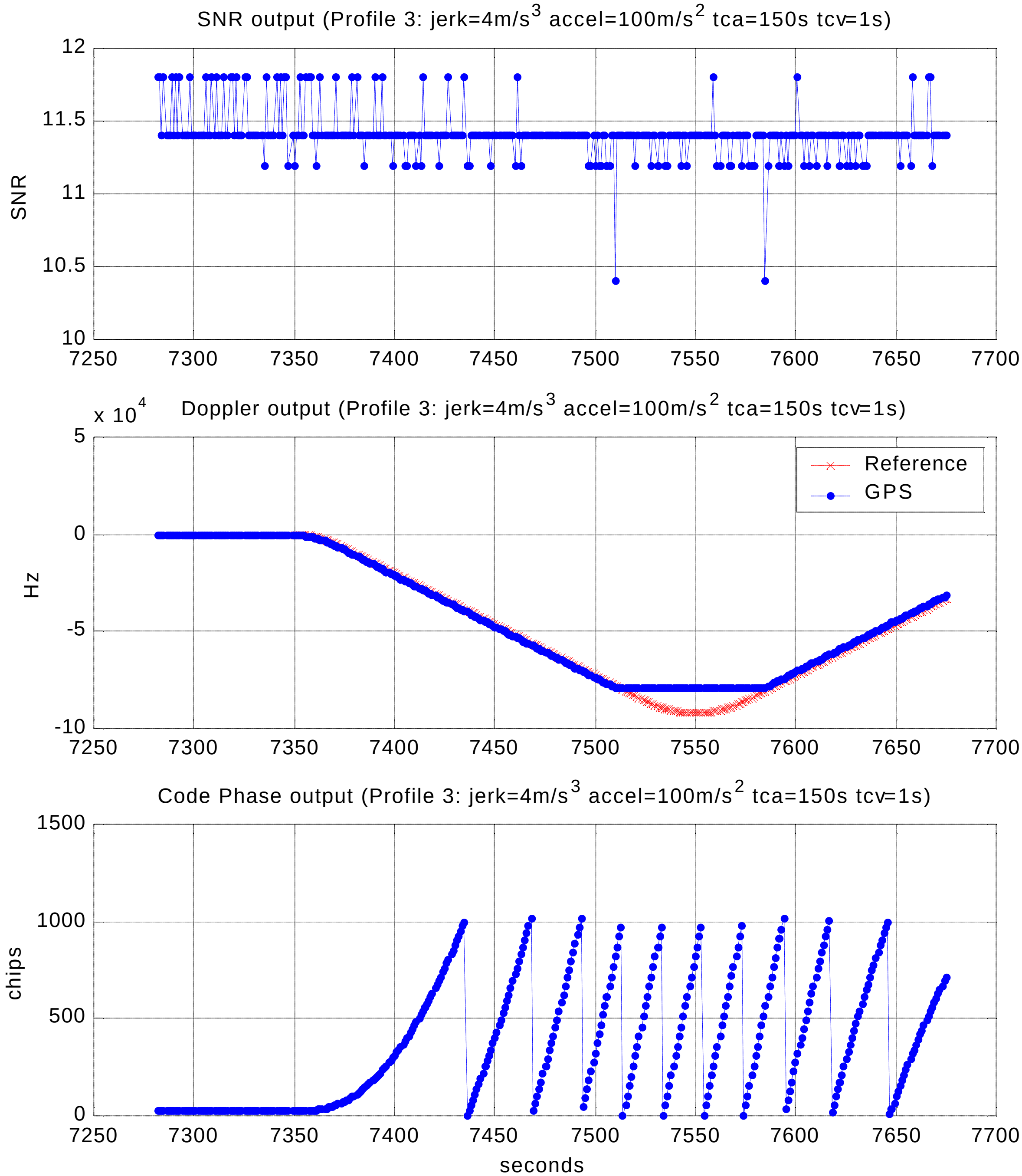
*** If this paper is revisited, future work should really include more detail and analysis of tracking loop performance and bandwidth. It might be difficult to experimentally determine any of the control loop design parameters without really knowing what kind of tracking implementation and control loop is in use in this receiver, yet classifying and understanding the limitations would be a step in the right direction.

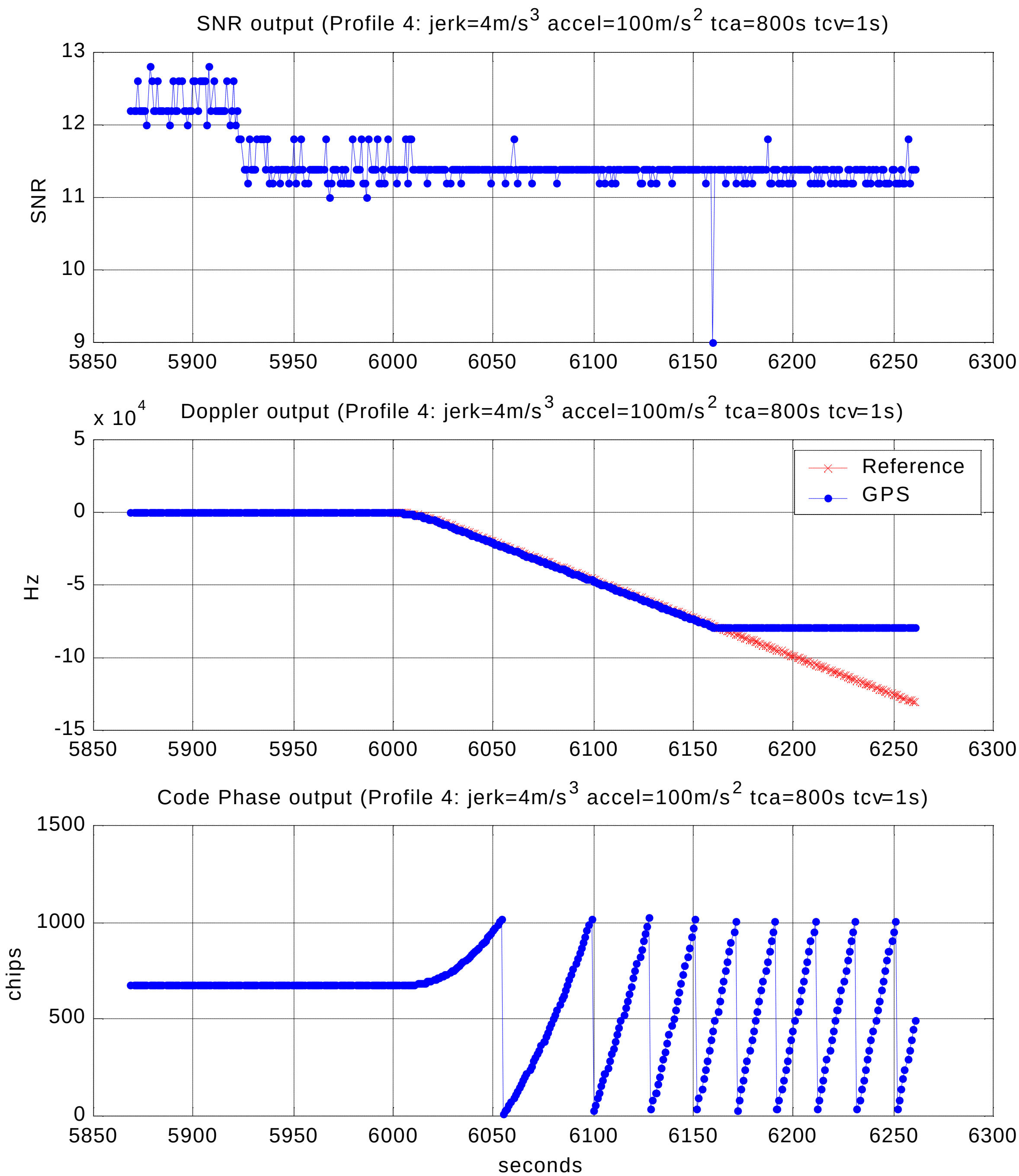
Appendix A

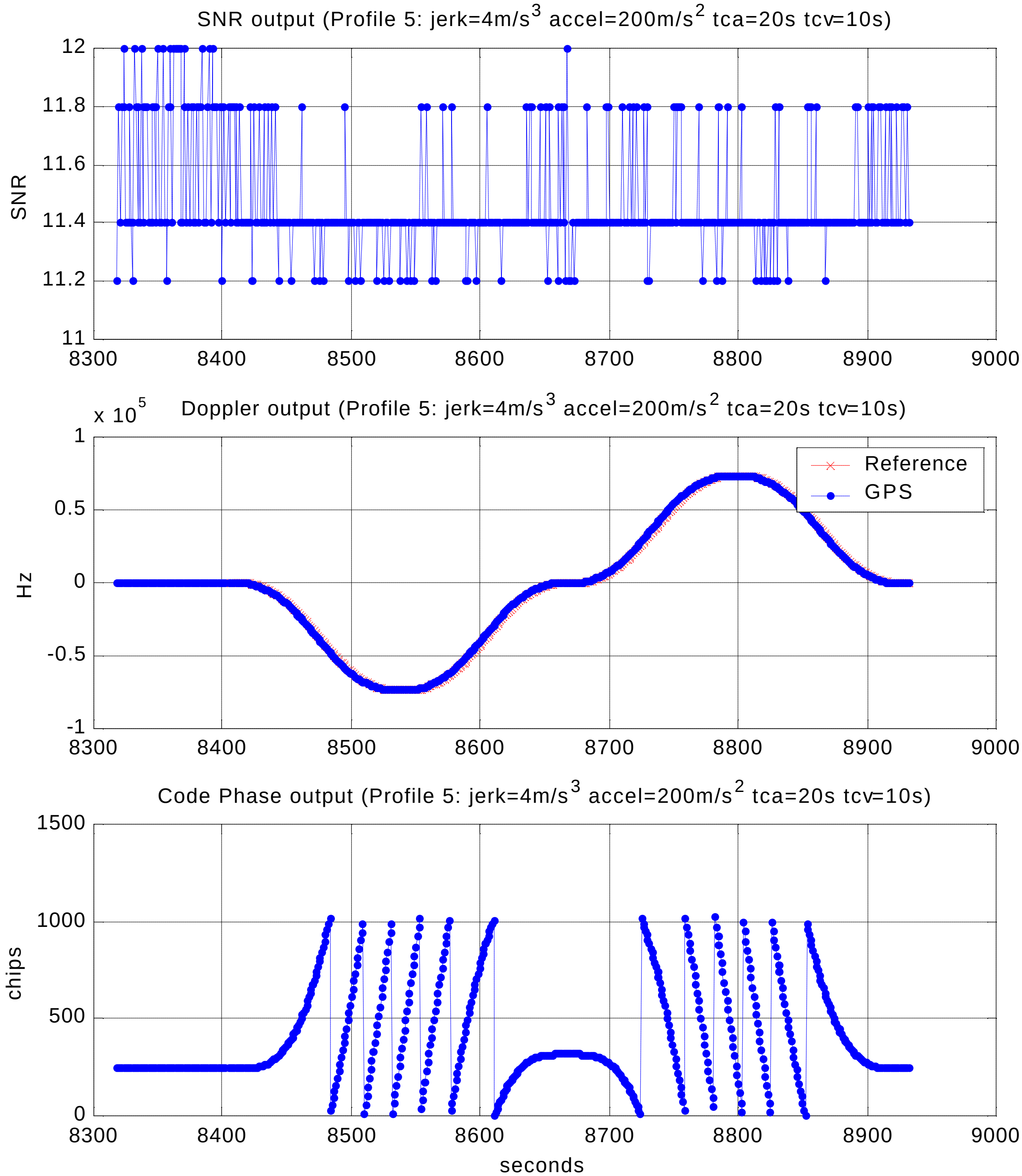
This appendix contains plots of the reference profile output as well as data gathered on GPS operation (signal SNR, Doppler output, and code phase output). Note that the discontinuities in code phase output on some plots is not an artifact of GPS instability but rather due to the aliasing of code phase output into the range of 0-1023 chips. In essence, the plots show absolute code phase mod 1023.



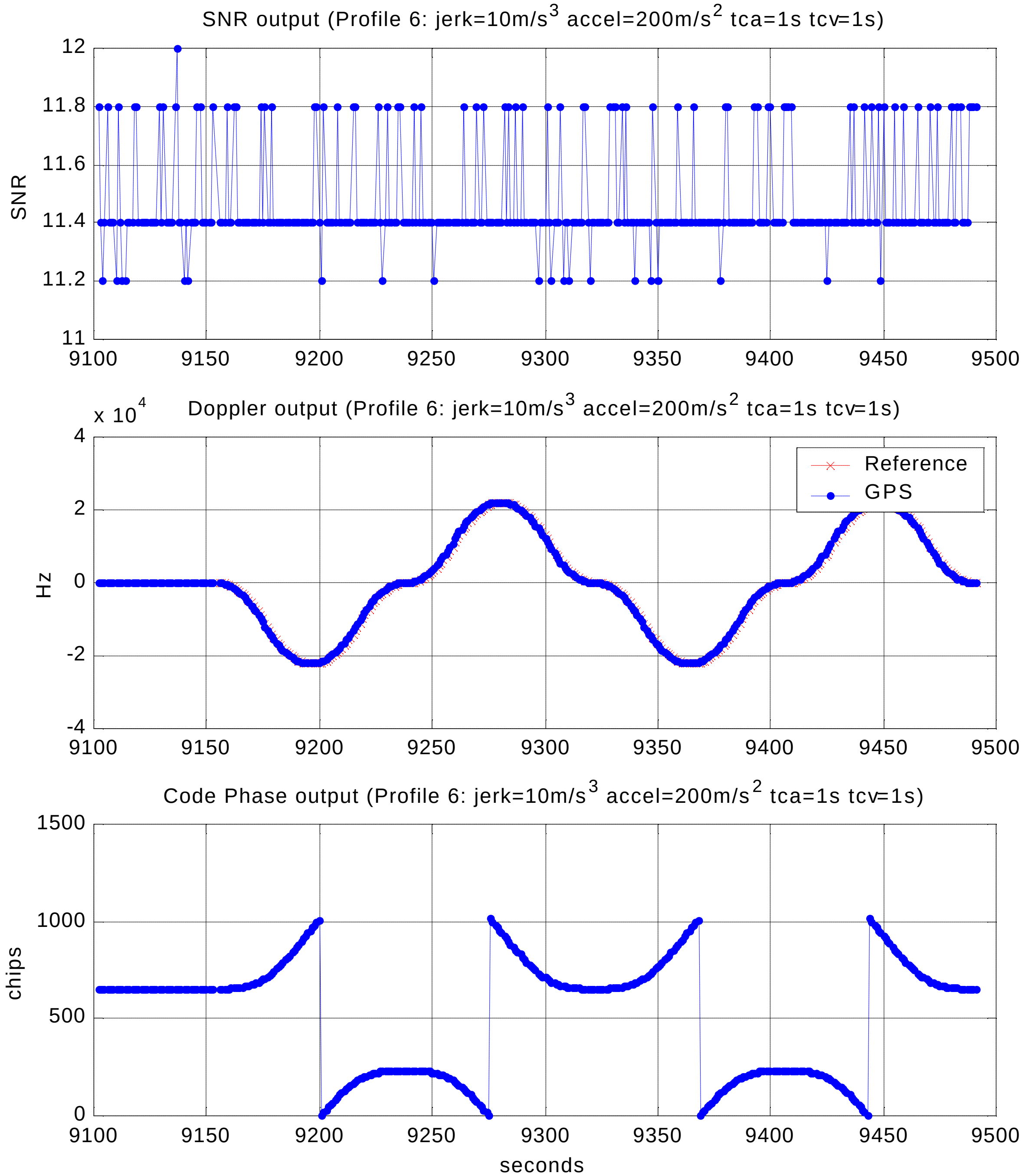

SNR output (Profile 2: jerk=2m/s3 accel=100m/s2 tca=40s tcv=10s)
SNR
12
11.5
11
10.5
10
9.5
300
400
500
600
700
800
900
1000
1100
Doppler output (Profile 2: jerk=2m/s3 accel=100m/s2 tca=40s tcv=10s)
x 10^4
5
0
-5
Hz
Reference
GPS
Code Phase output (Profile 2: jerk=2m/s3 accel=100m/s2 tca=40s tcv=10s)
chips
1500
1000
500
0
seconds


SNR output (Profile 3: jerk=4m/s^3 accel=100m/s^2 tca=150s tcv=1s)
SNR
12
11.5
11
10.5
10
7250
7300
7350
7400
7450
7500
7550
7600
7650
7700
x 10^4
Doppler output (Profile 3: jerk=4m/s^3 accel=100m/s^2 tca=150s tcv=1s)
Hz
5
0
-5
-10
Reference
GPS
Code Phase output (Profile 3: jerk=4m/s^3 accel=100m/s^2 tca=150s tcv=1s)
chips
1500
1000
500
0
seconds

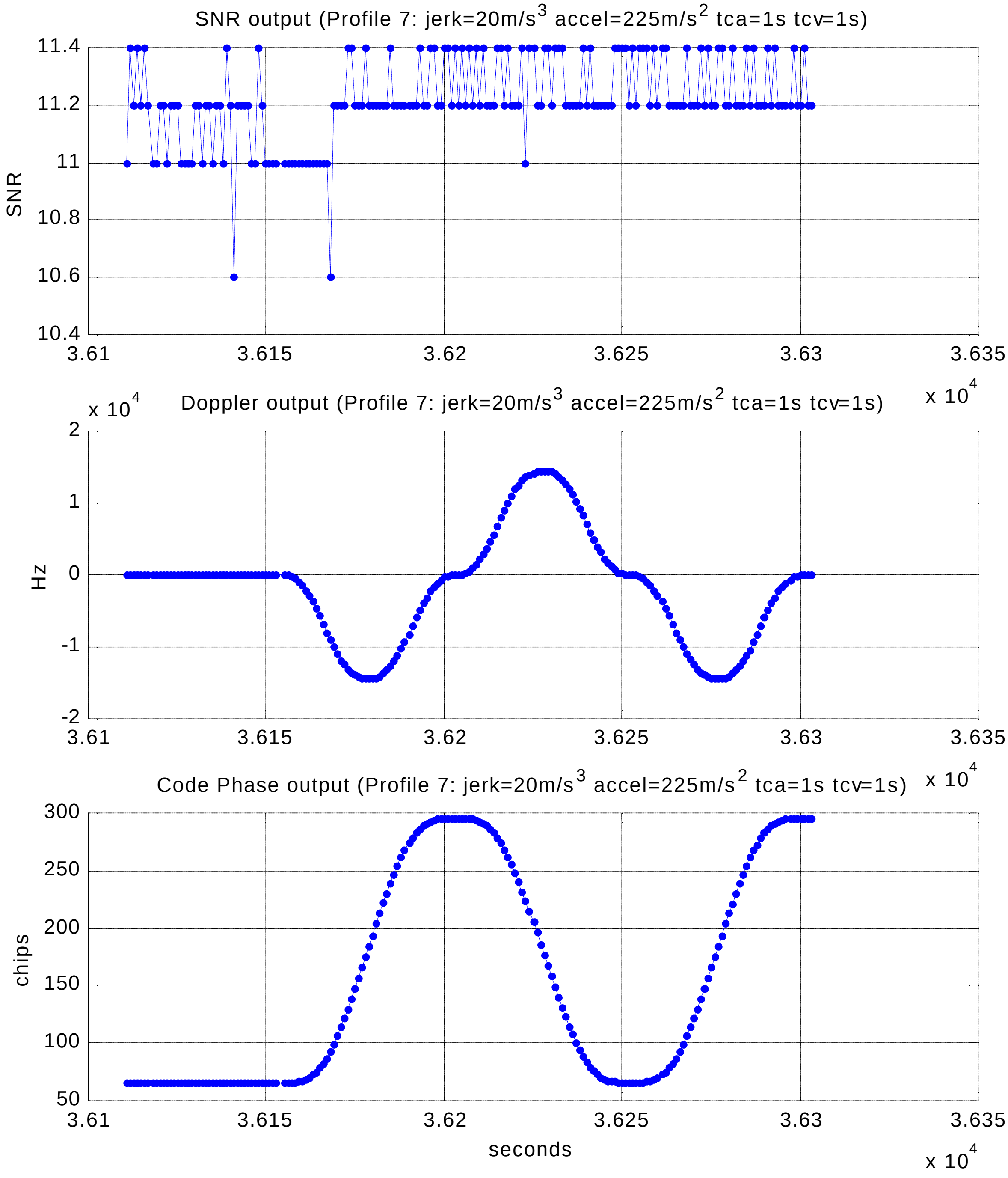

SNR output (Profile 4: jerk=4m/s^3 accel=100m/s^2 tca=800s tcv=1s)
SNR
13
12
11
10
9
5850
5900
5950
6000
6050
6100
6150
6200
6250
6300
x 10^4
Doppler output (Profile 4: jerk=4m/s^3 accel=100m/s^2 tca=800s tcv=1s)
Hz
5
0
-5
-10
-15
Reference
GPS
Code Phase output (Profile 4: jerk=4m/s^3 accel=100m/s^2 tca=800s tcv=1s)
chips
1500
1000
500
0
seconds

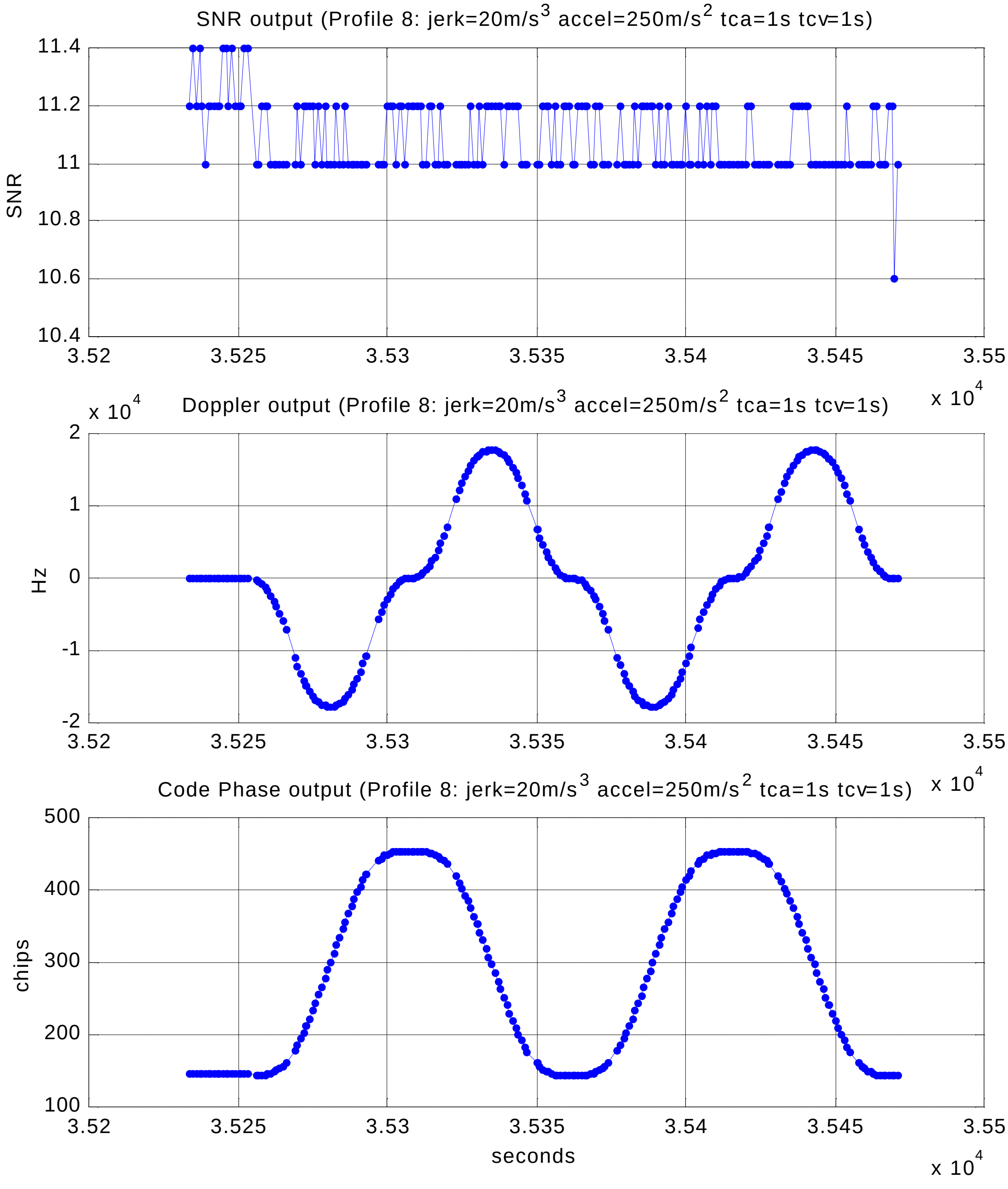


SNR output (Profile 5: jerk=4m/s3 accel=200m/s2 tca=20s tcv=10s)
SNR
12
11.8
11.6
11.4
11.2
11
8300
8400
8500
8600
8700
8800
8900
9000
x 10^5
Doppler output (Profile 5: jerk=4m/s3 accel=200m/s2 tca=20s tcv=10s)
Reference
GPS
Hz
1
0.5
0
-0.5
-1
Code Phase output (Profile 5: jerk=4m/s3 accel=200m/s2 tca=20s tcv=10s)
chips
1500
1000
500
0
seconds

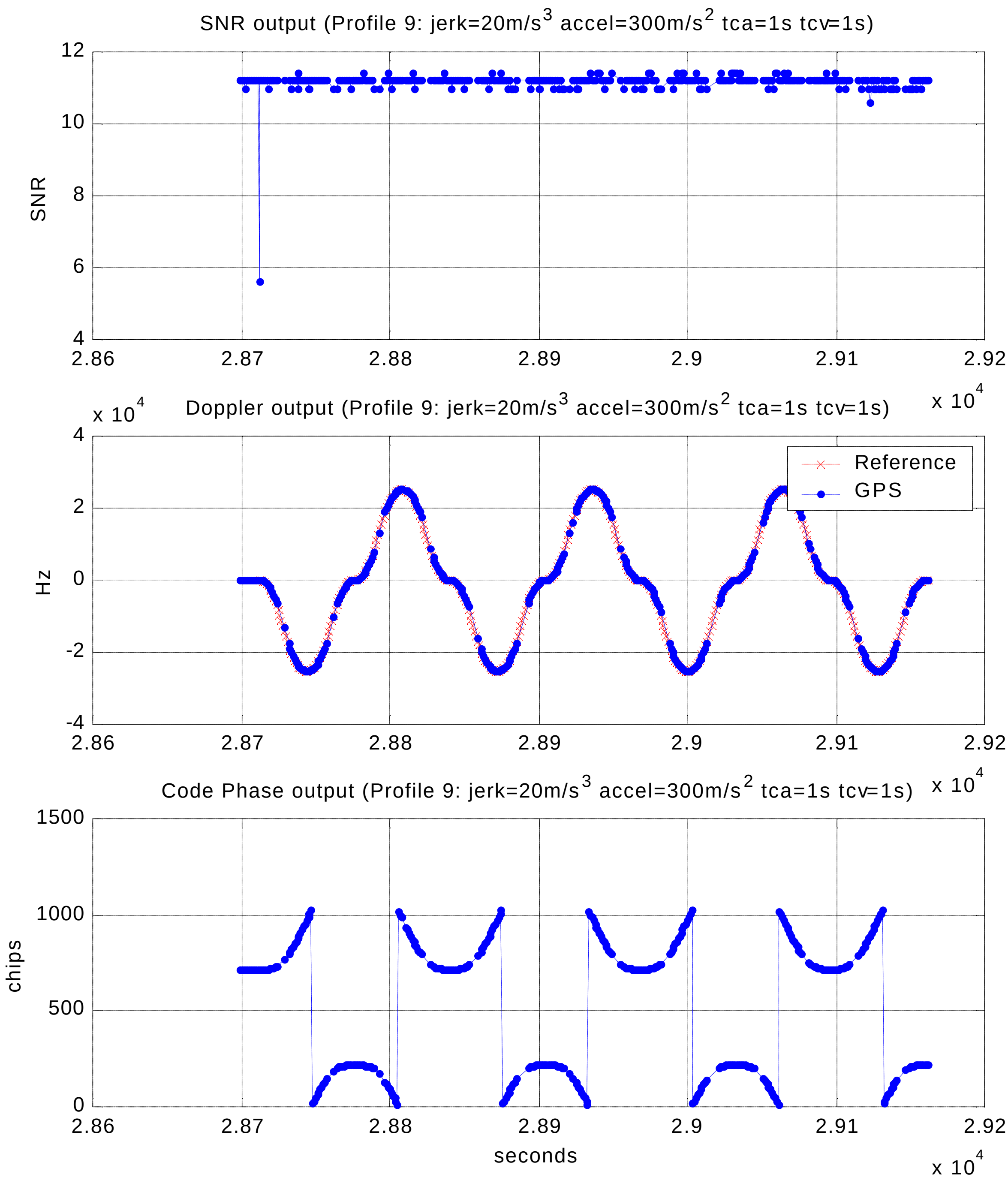


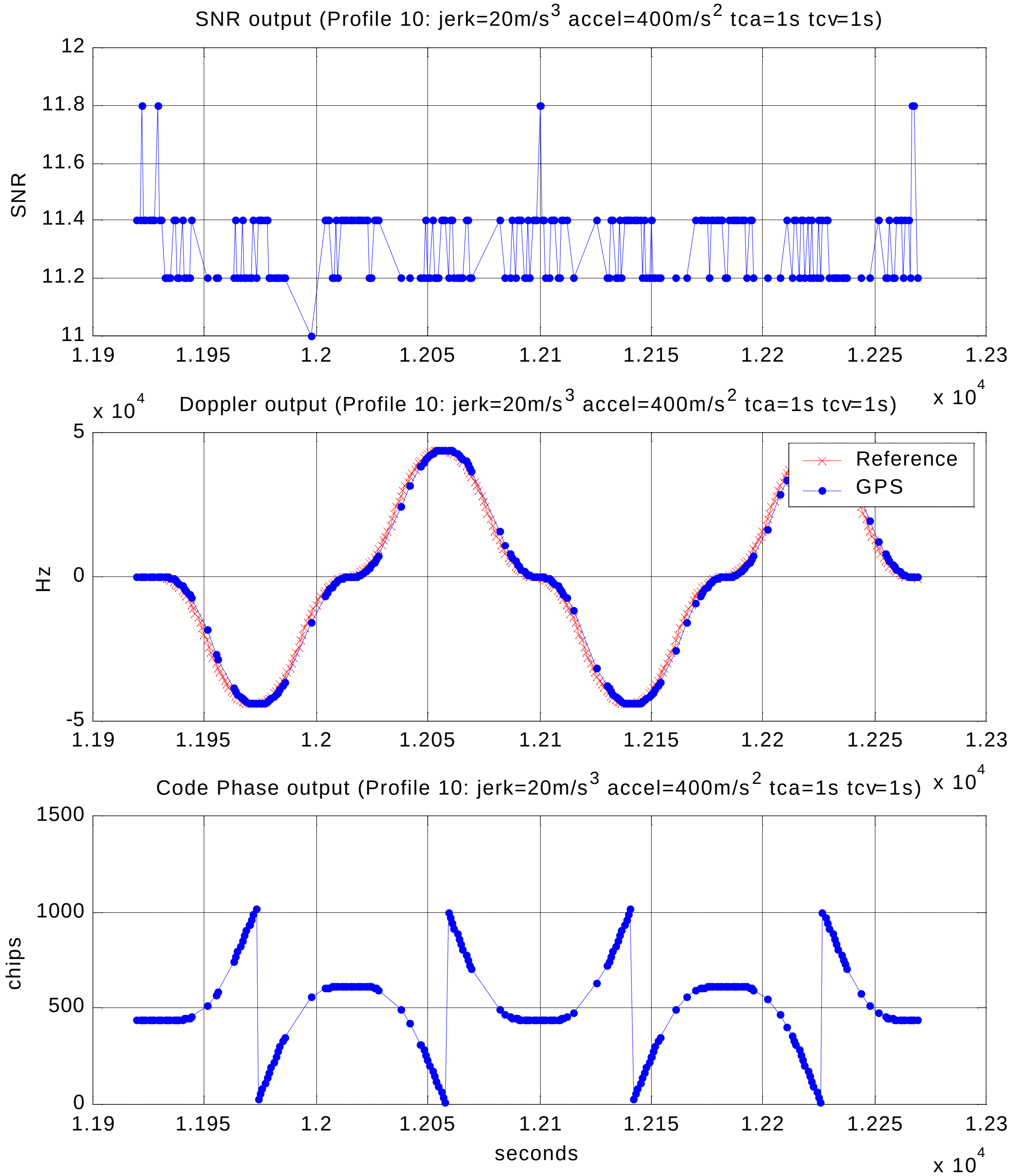
SNR output (Profile 6: jerk=10m/s3 accel=200m/s2 tca=1s tcv=1s)
SNR
12
11.8
11.6
11.4
11.2
11
9100 9150 9200 9250 9300 9350 9400 9450 9500
Doppler output (Profile 6: jerk=10m/s3 accel=200m/s2 tca=1s tcv=1s)
x 10^4
Hz
4
2
0
-2
-4
Reference
GPS
9100 9150 9200 9250 9300 9350 9400 9450 9500
Code Phase output (Profile 6: jerk=10m/s3 accel=200m/s2 tca=1s tcv=1s)
chips
1500
1000
500
0
9100 9150 9200 9250 9300 9350 9400 9450 9500
seconds


SNR output (Profile 7: jerk=20m/s^3 accel=225m/s^2 tca=1s tcv=1s)
SNR
11.4
11.2
11
10.8
10.6
10.4
3.61
3.615
3.62
3.625
3.63
3.635
x 10^4
Doppler output (Profile 7: jerk=20m/s^3 accel=225m/s^2 tca=1s tcv=1s)
x 10^4
Hz
2
1
0
-1
-2
3.61
3.615
3.62
3.625
3.63
3.635
x 10^4
Code Phase output (Profile 7: jerk=20m/s^3 accel=225m/s^2 tca=1s tcv=1s)
chips
300
250
200
150
100
50
3.61
3.615
3.62
3.625
3.63
3.635
seconds
x 10^4

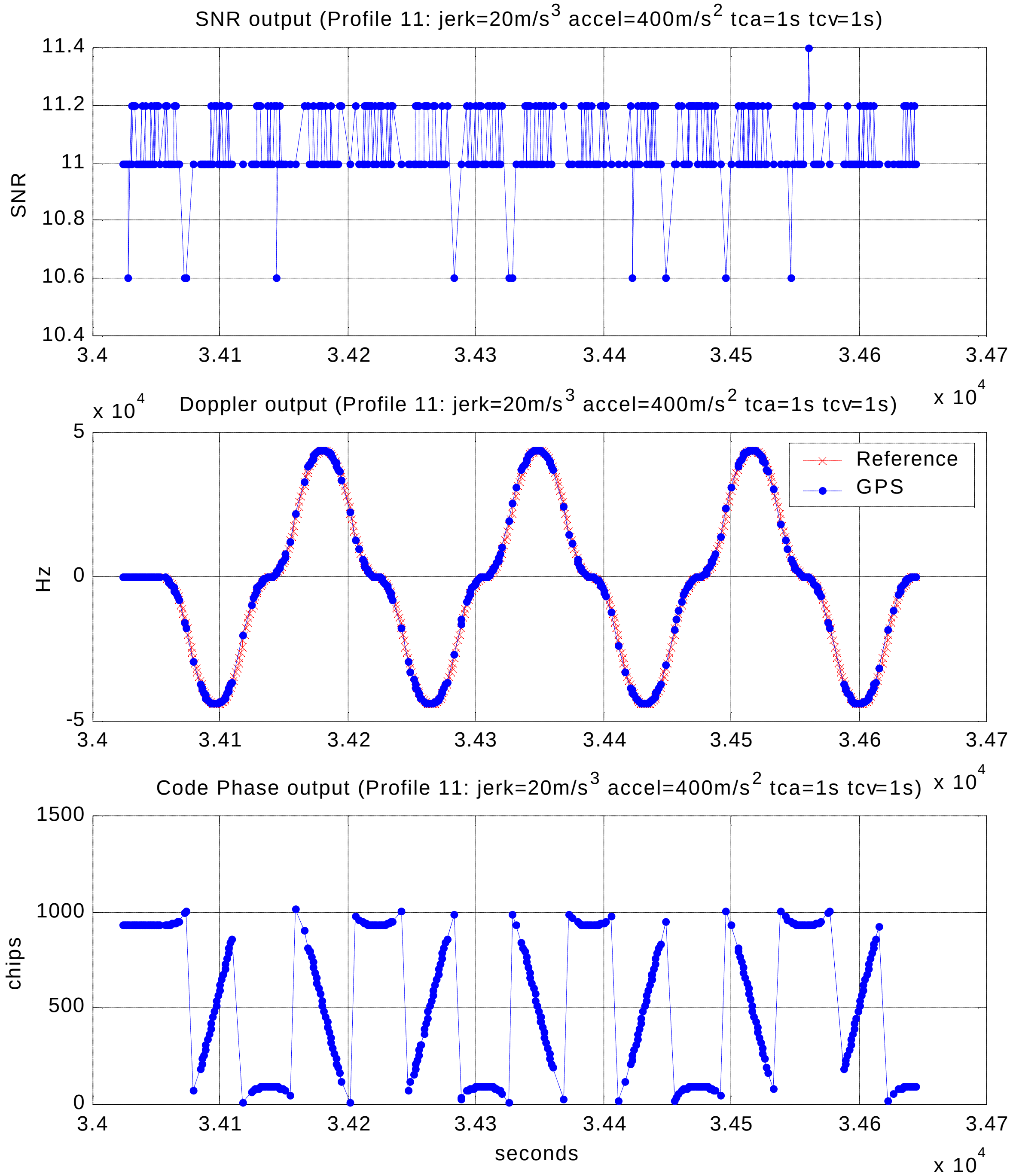


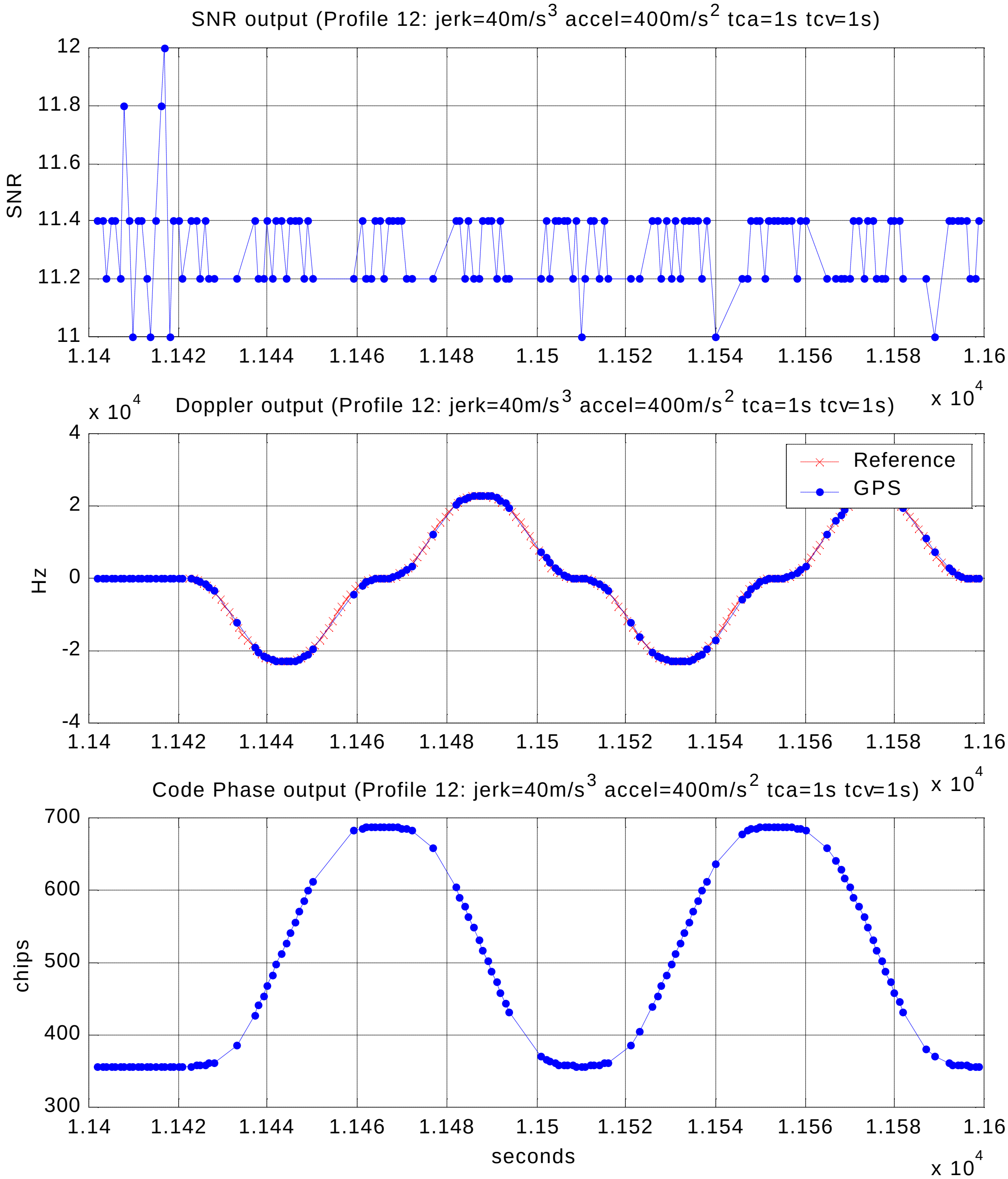
SNR output (Profile 8: jerk=20m/s3 accel=250m/s2 tca=1s tcv=1s)
SNR
11.4
11.2
11
10.8
10.6
10.4
3.52
3.525
3.53
3.535
3.54
3.545
3.55
x 10^4
Doppler output (Profile 8: jerk=20m/s3 accel=250m/s2 tca=1s tcv=1s)
x 10^4
Hz
2
1
0
-1
-2
Code Phase output (Profile 8: jerk=20m/s3 accel=250m/s2 tca=1s tcv=1s)
chips
500
400
300
200
100
seconds


SNR output (Profile 9: jerk=20m/s3 accel=300m/s2 tca=1s tcv=1s)
SNR
12
10
8
6
4
2.86
2.87
2.88
2.89
2.9
2.91
2.92
x 104
Doppler output (Profile 9: jerk=20m/s3 accel=300m/s2 tca=1s tcv=1s)
x 104
Hz
4
2
0
-2
-4
Reference
GPS
Code Phase output (Profile 9: jerk=20m/s3 accel=300m/s2 tca=1s tcv=1s)
chips
1500
1000
500
0
seconds



SNR output (Profile 10: jerk=20m/s3 accel=400m/s2 tca=1s tcv=1s)
SNR
12
11.8
11.6
11.4
11.2
11
1.19
1.195
1.2
1.205
1.21
1.215
1.22
1.225
1.23
x 10^4
Doppler output (Profile 10: jerk=20m/s3 accel=400m/s2 tca=1s tcv=1s)
x 10^4
Hz
5
0
-5
Reference
GPS
1.19
1.195
1.2
1.205
1.21
1.215
1.22
1.225
1.23
x 10^4
Code Phase output (Profile 10: jerk=20m/s3 accel=400m/s2 tca=1s tcv=1s)
chips
1500
1000
500
0
1.19
1.195
1.2
1.205
1.21
1.215
1.22
1.225
1.23
seconds
x 10^4


SNR output (Profile 11: jerk=20m/s3 accel=400m/s2 tca=1s tcv=1s)
SNR
11.4
11.2
11
10.8
10.6
10.4
3.4
3.41
3.42
3.43
3.44
3.45
3.46
3.47
x 10^4
Doppler output (Profile 11: jerk=20m/s3 accel=400m/s2 tca=1s tcv=1s)
x 10^4
Hz
5
0
-5
Reference
GPS
Code Phase output (Profile 11: jerk=20m/s3 accel=400m/s2 tca=1s tcv=1s)
chips
1500
1000
500
0
seconds


SNR output (Profile 12: jerk=40m/s3 accel=400m/s2 tca=1s tcv=1s)
SNR
Doppler output (Profile 12: jerk=40m/s3 accel=400m/s2 tca=1s tcv=1s)
Hz
x 10^4
Reference
GPS
Code Phase output (Profile 12: jerk=40m/s3 accel=400m/s2 tca=1s tcv=1s)
chips
seconds
x 10^4