



# **GPS Beamforming with Low-cost RTL-SDRs**

**Wil Myrick, Ph.D.**

September 13, 2017  
GNU Radio Conference 2017

# Recap from GRCon 2016

MWF Invented by Dr. Scott Goldstein and Dr. Irving Reed (1996)

GNU Radio Initial Release (2001)

Revisited GPS Work and GNU Radio (2013)

Asynchronous Distributed Sensor Processing with FM SoOPs (2014)

Embedded GPS Research (2015)

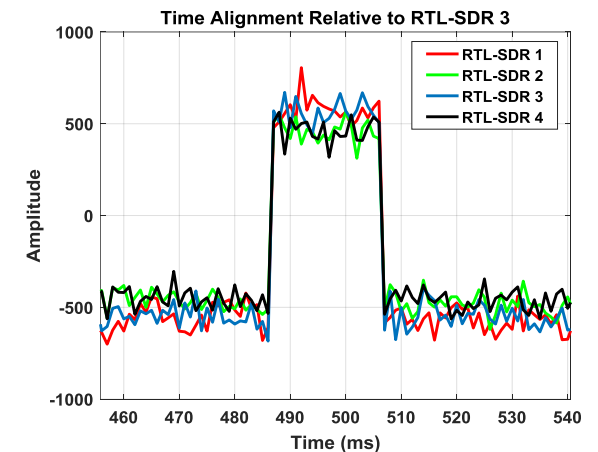
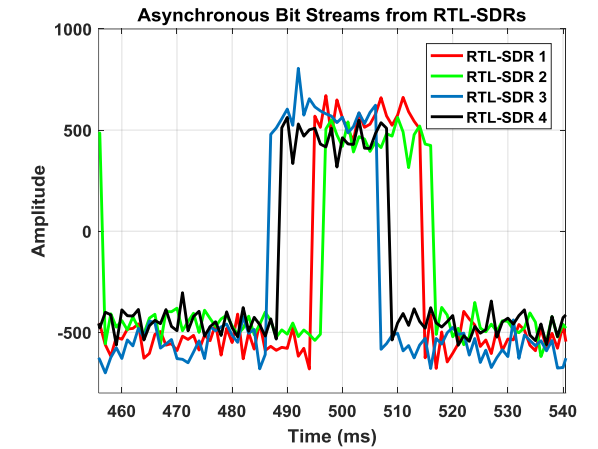
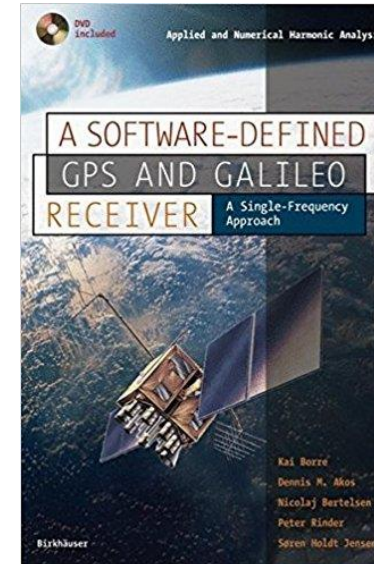
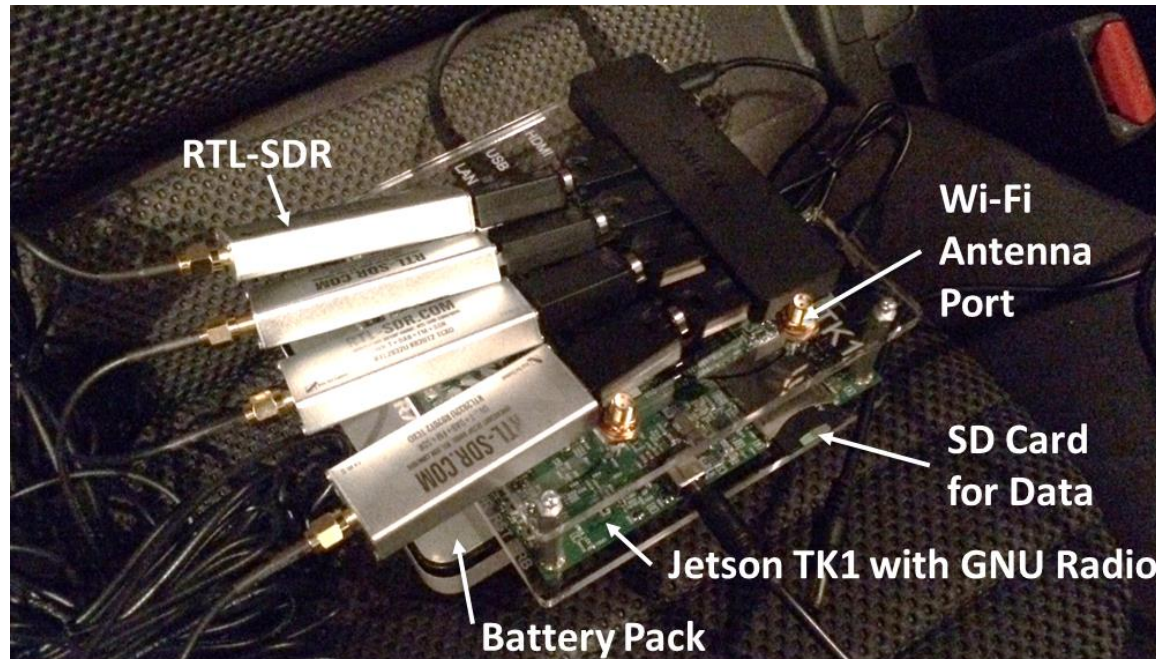
GNSS-SDR GPS Processing

Timeline of Signal Processing Experience

Completed MWF based GPS STAP Ph.D. Thesis with Dr. Michael Zoltowski (2000)



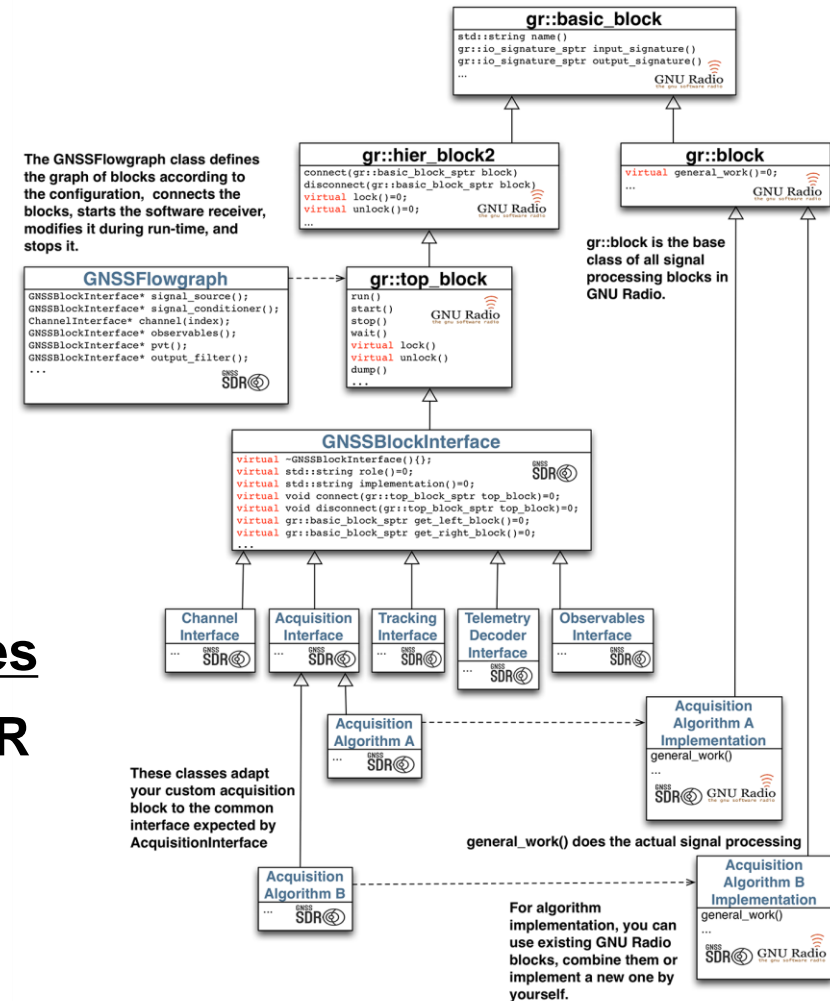
+



Adjust the frequencies and phases based on tracking information from the RTL-SDRs

# From GRCon16 to GRCon17

- ✓ Streamed 60 seconds of data from each RTL-SDR (2016)
- ✓ Demodulated navigation data for each detected channel (2016)
- ✓ Tracked delay, frequency, and phase from each RTL-SDR (2016)
- ✓ Time, frequency, and phase alignment based on RTL-SDRs sharing no common external references
- ✓ RTL-SDR based GPS beamformer with GNSS-SDR
- ✓ GPS position estimates from beamformed RTL-SDRs
- ✓ GNSS-SDR on Raspberry Pi 3



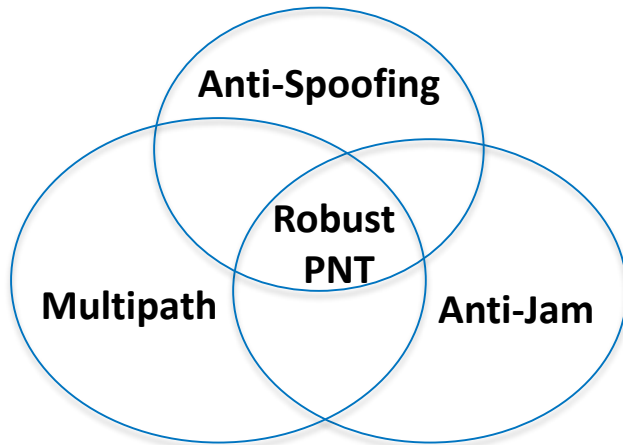
## GNU Radio Receiver based on GNSS-SDR Framework (CTTC)

- Built on GNU Radio blocks
- Supports real-time positioning based on RTL-SDRs
- Supports custom algorithm integration

<http://gnss-sdr.org/documentation/how-gnss-sdr-works>

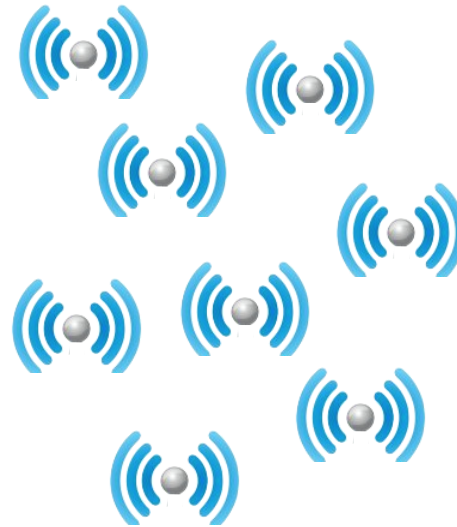
# Robust Positioning, Navigation, and Timing (PNT)

## Standard Beamforming Solutions



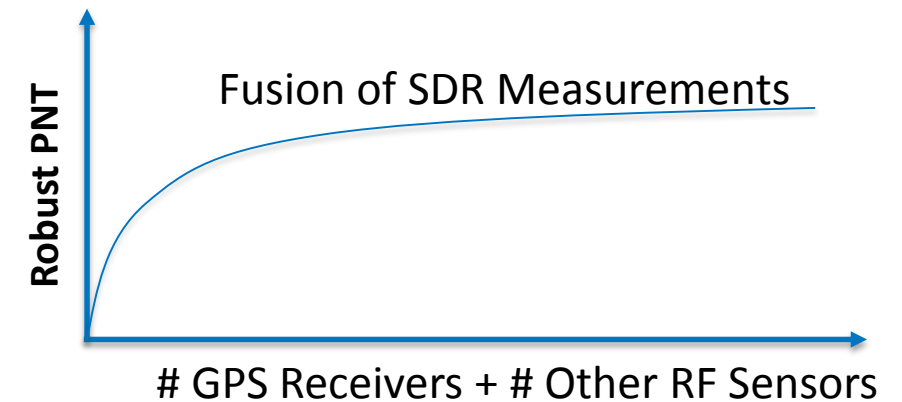
Spatial Beamforming enables a variety of solutions that provide Robust PNT on single platforms

## IoT Devices



IoT devices with low SWAP-C could share PNT information potentially providing Robust PNT solutions for a group of IoT Devices

## Explore Distributed GPS Beamforming with a Variety of SDRs



Low Swap-C  
RTL-SDR

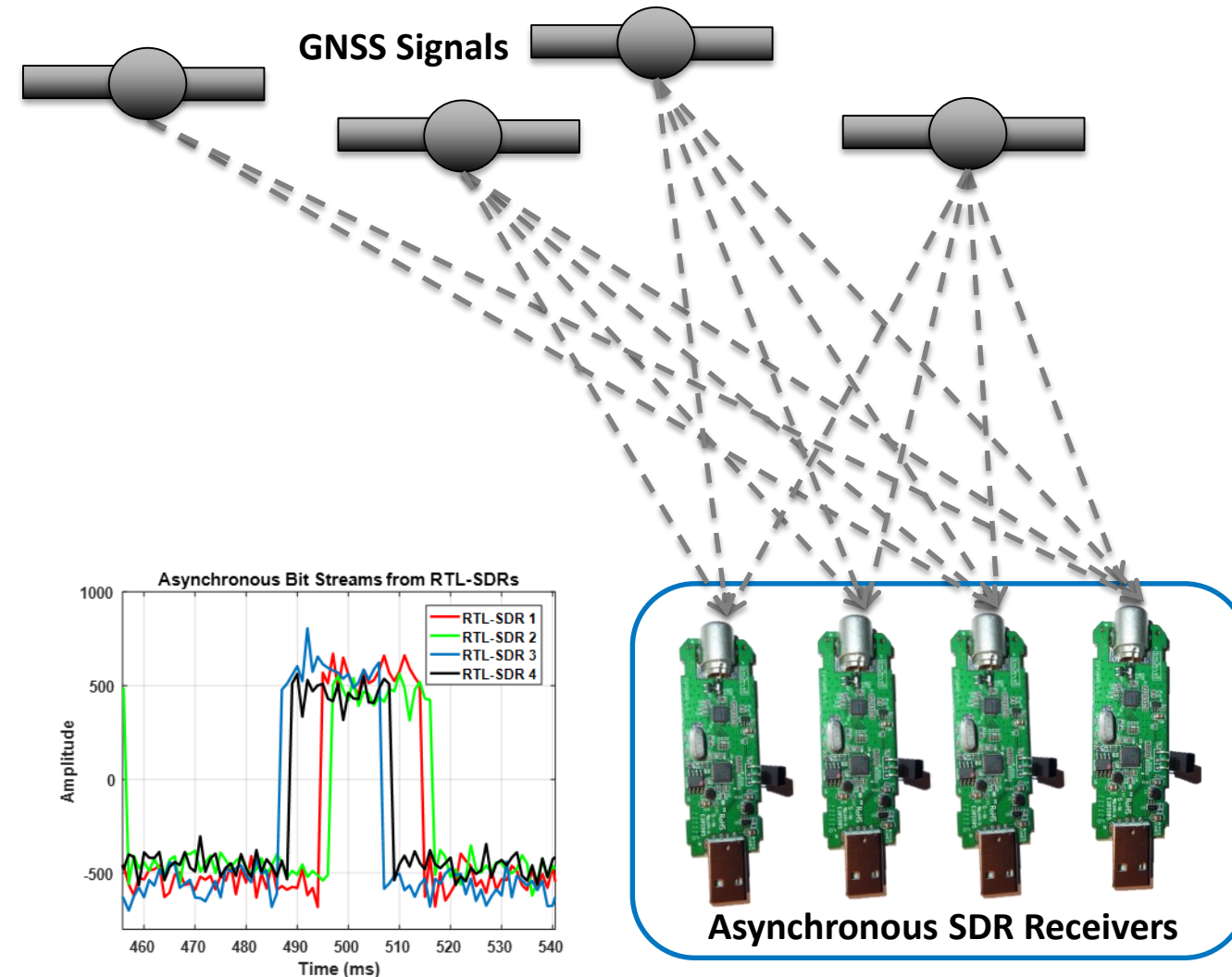


ENSCO  
TCR-D



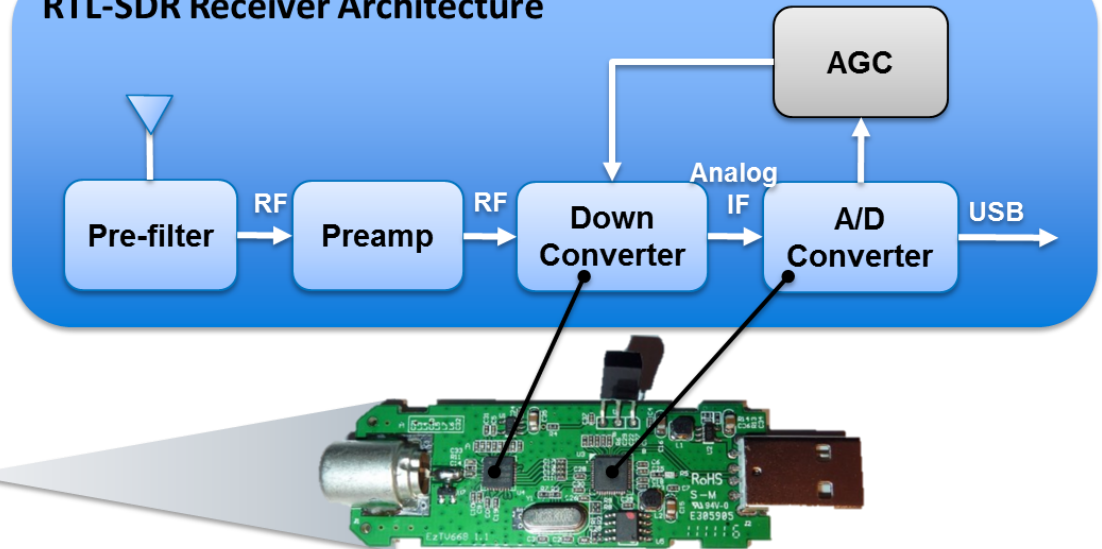


# GPS Beamforming with RTL-SDRs



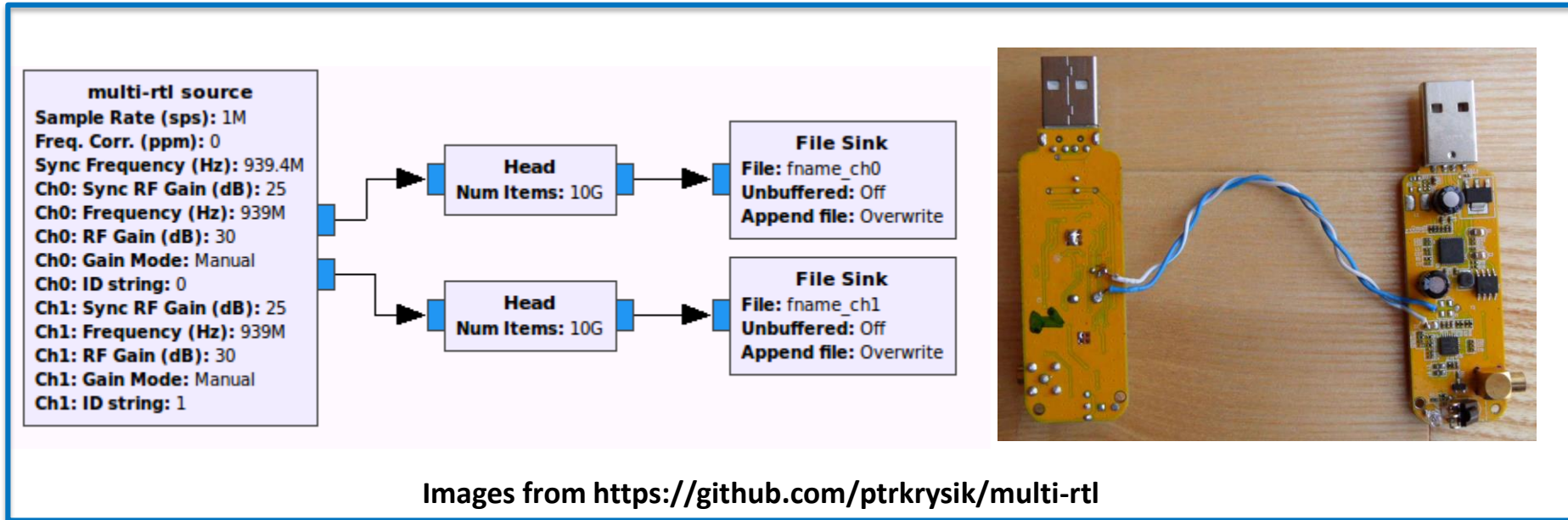
Low-Cost RTL-SDRs Lack External Clock Inputs

RTL-SDR Receiver Architecture



# Typical Approaches to Synchronizing RTL-SDRs

## Multi-RTL Approach

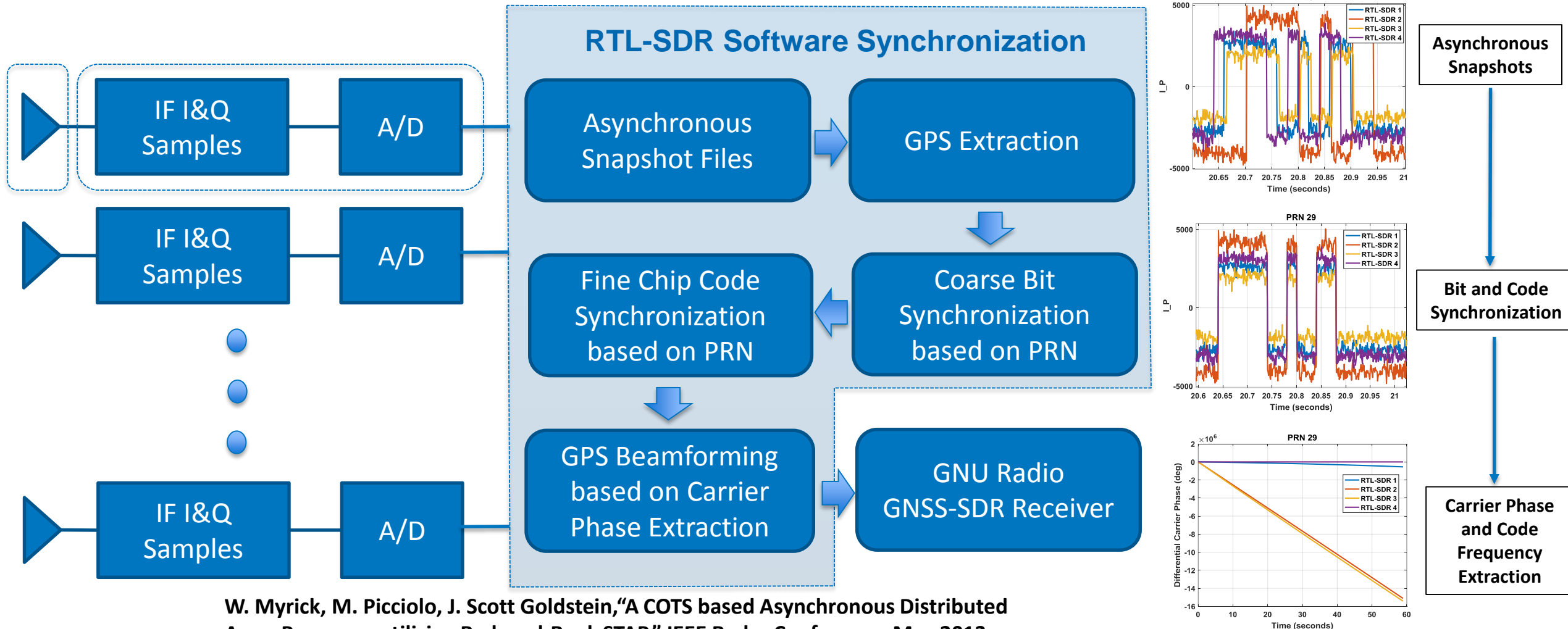


Typical approaches to leveraging multiple RTL-SDRs involve hardware modifications so a single clock source is shared between the RTL-SDRs

“Multi-RTL is GNU Radio block that transforms cheap multiple RTL-SDR receivers into multi-channel receiver” Reference: <https://github.com/ptrkrysik/multi-rtl>

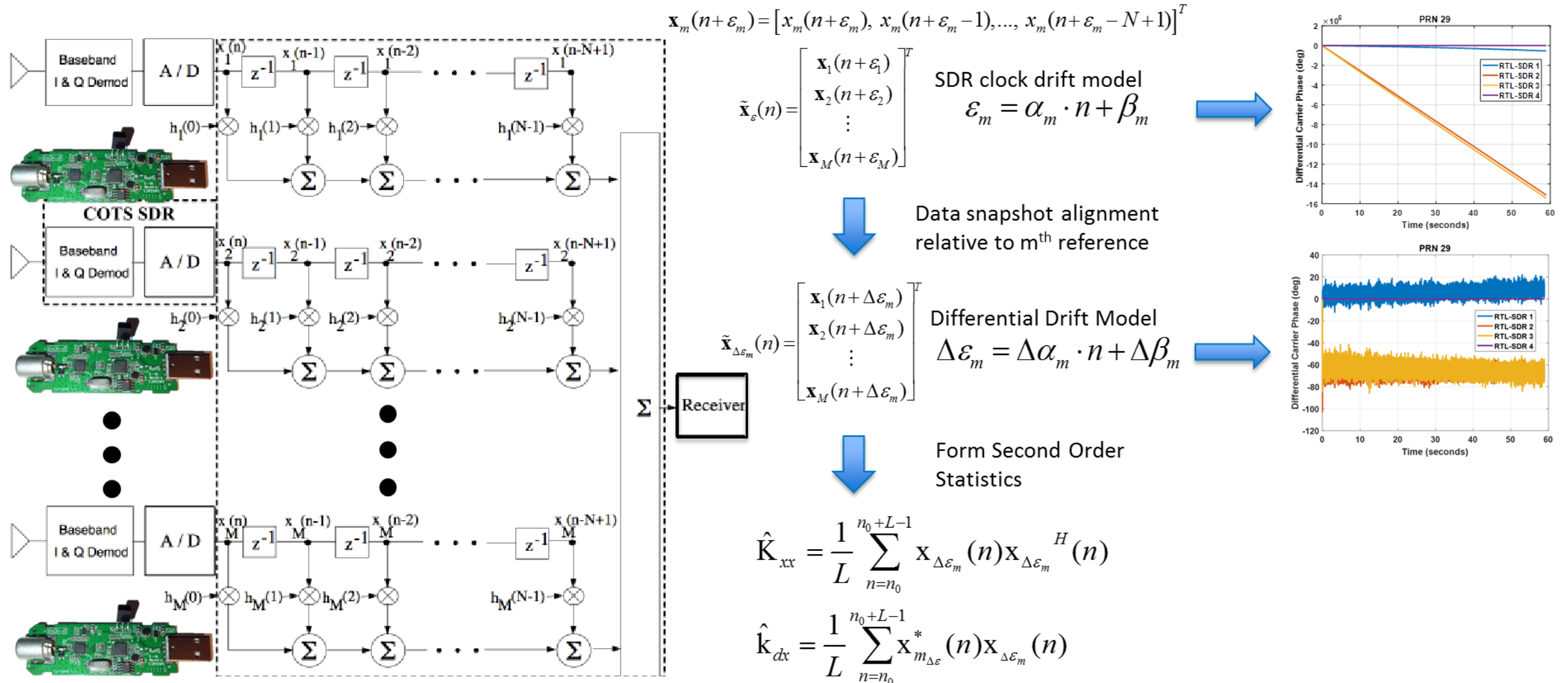
Other References: <http://superkuh.com/rtlSdr.html#clocks.align.multirtl>

# Overall RTL-SDR “Software” Synchronization Approach



W. Myrick, M. Picciolo, J. Scott Goldstein, “A COTS based Asynchronous Distributed Array Processor utilizing Reduced-Rank STAP,” IEEE Radar Conference, May 2013

# RTL-SDR “Software” Synchronization Approach





# Asynchronous Snapshots with RTL-SDRs

## RTL-SDR Software Synchronization

Asynchronous  
Snapshot Files

GPS Extraction

Fine Chip Code  
Synchronization  
based on PRN

Coarse Bit  
Synchronization  
based on PRN

GPS Beamforming  
based on Carrier  
Phase Extraction

GNU Radio  
GNSS-SDR Receiver

```
myrickw — pi@raspberrypi: ~ — ssh pi@192.168.0.1 — 92x10
rtl_sdr -s 2400000 -f 1575420000 -g 49.6 temp_1.bin -d 0 -n 144000000 & rtl_sdr -s 2400000 -f 1575420000 -g 49.6 temp_2.bin -d 1 -n 144000000 & rtl_sdr -s 2400000 -f 1575420000 -g 49.6 temp_3.bin -d 2 -n 144000000 & rtl_sdr -s 2400000 -f 1575420000 -g 49.6 temp_4.bin -d 3 -n 144000000
```

Script to capture 60 seconds of GPS data from RTL-SDRs

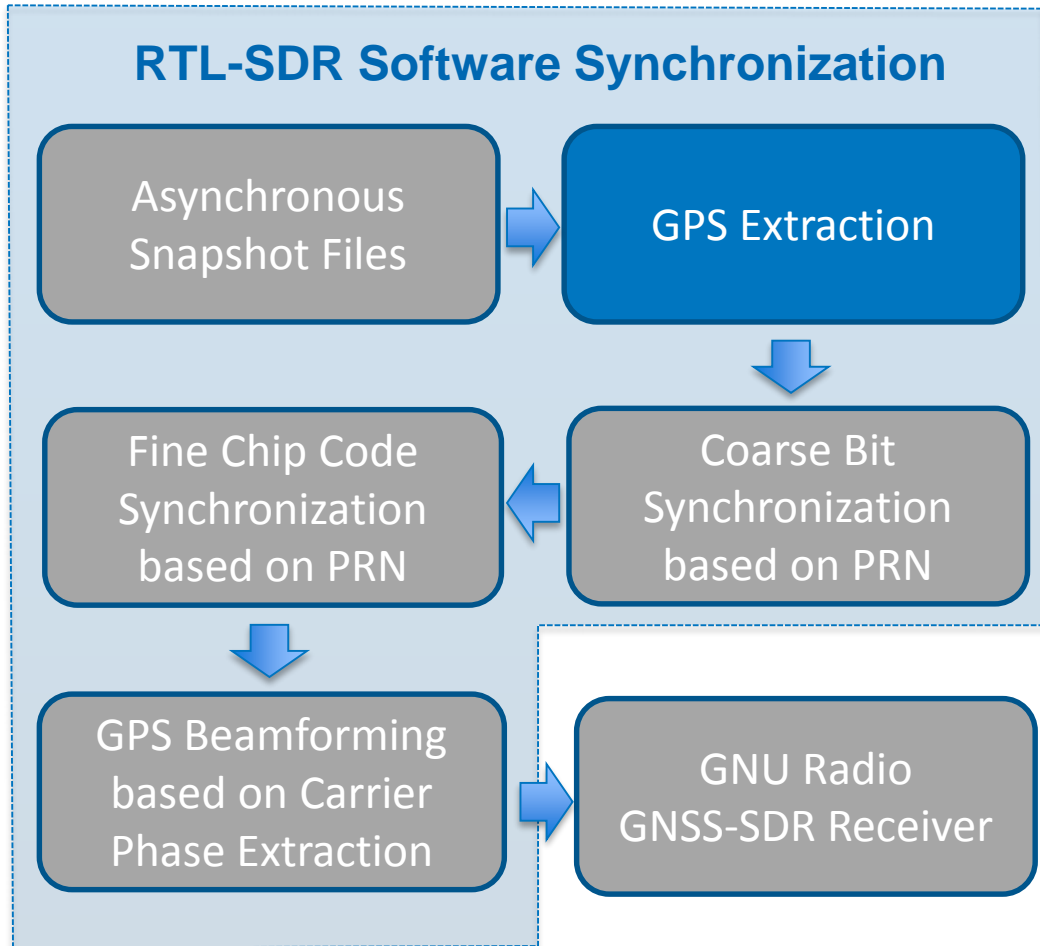
RTL-SDR1\_file\_async  
RTL-SDR2\_file\_async  
RTL-SDR3\_file\_async  
RTL-SDR4\_file\_async

Synchronization of  
RTL-SDRs relative  
to RTL-SDR4

RTL-SDR1\_file\_sync  
RTL-SDR2\_file\_sync  
RTL-SDR3\_file\_sync  
RTL-SDR4\_file\_async

RTL-SDR data files are synchronized relative to RTL-SDR4 after RTL-SDR software synchronization

# GPS Acquisition across RTL-SDRs



## RTL-SDRs provide varying GPS acquisition results

RTL-SDR 1	RTL-SDR 2	RTL-SDR 3	RTL-SDR 4
13	13	13	13
15	15	15	15
29*	29*	29*	29*
2	-	2	2
5	5	5	5
20	20	-	20

\* PRN 29 was used as reference transmitter for RTL-SDR synchronization

# Coarse (Data) and Fine (Code) Synchronization

## RTL-SDR Software Synchronization

Asynchronous  
Snapshot Files

GPS Extraction

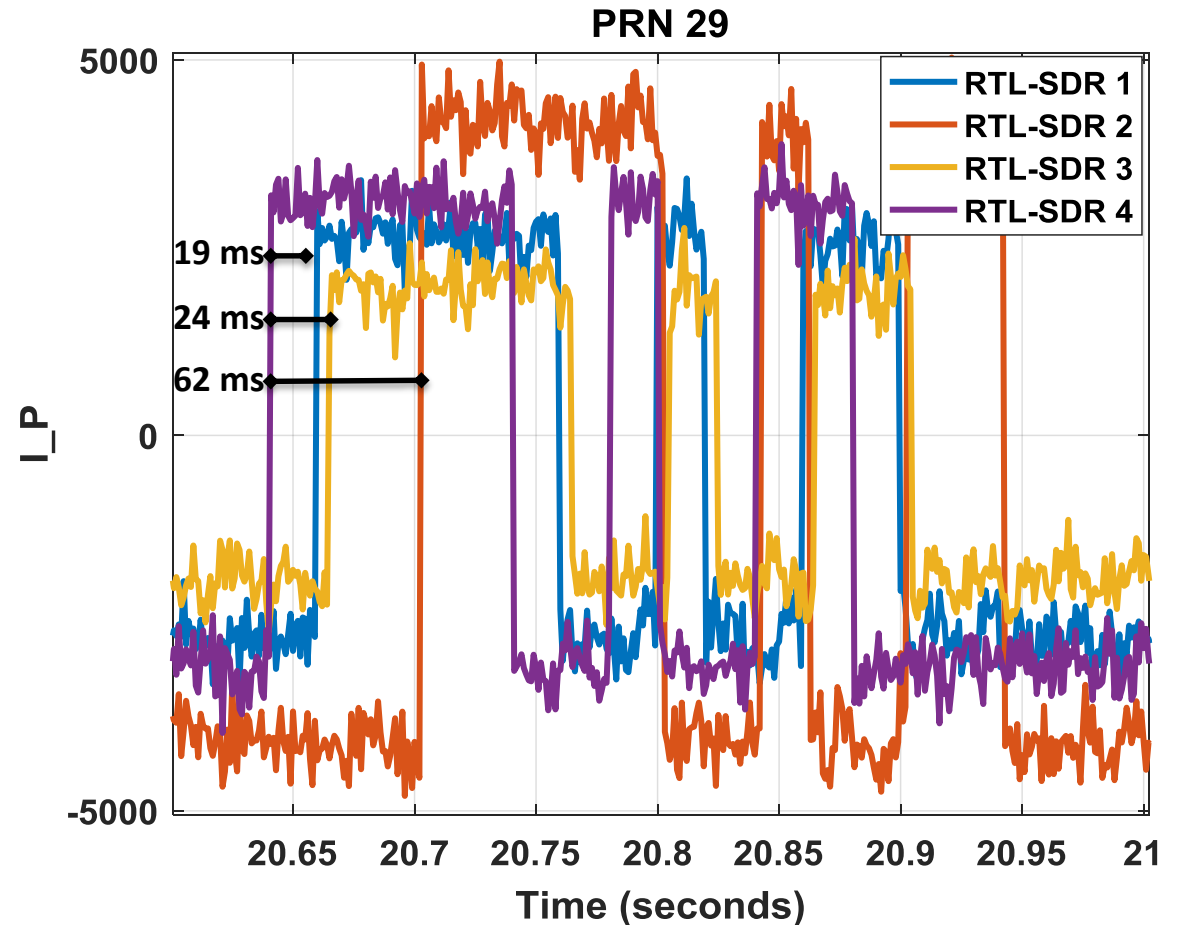
Fine Chip Code  
Synchronization  
based on PRN

Coarse Bit  
Synchronization  
based on PRN

GPS Beamforming  
based on Carrier  
Phase Extraction

GNU Radio  
GNSS-SDR Receiver

## Leverage RTL-SDR 4 as the reference



# Coarse (Data) and Fine (Code) Synchronization

## RTL-SDR Software Synchronization

Asynchronous  
Snapshot Files

GPS Extraction

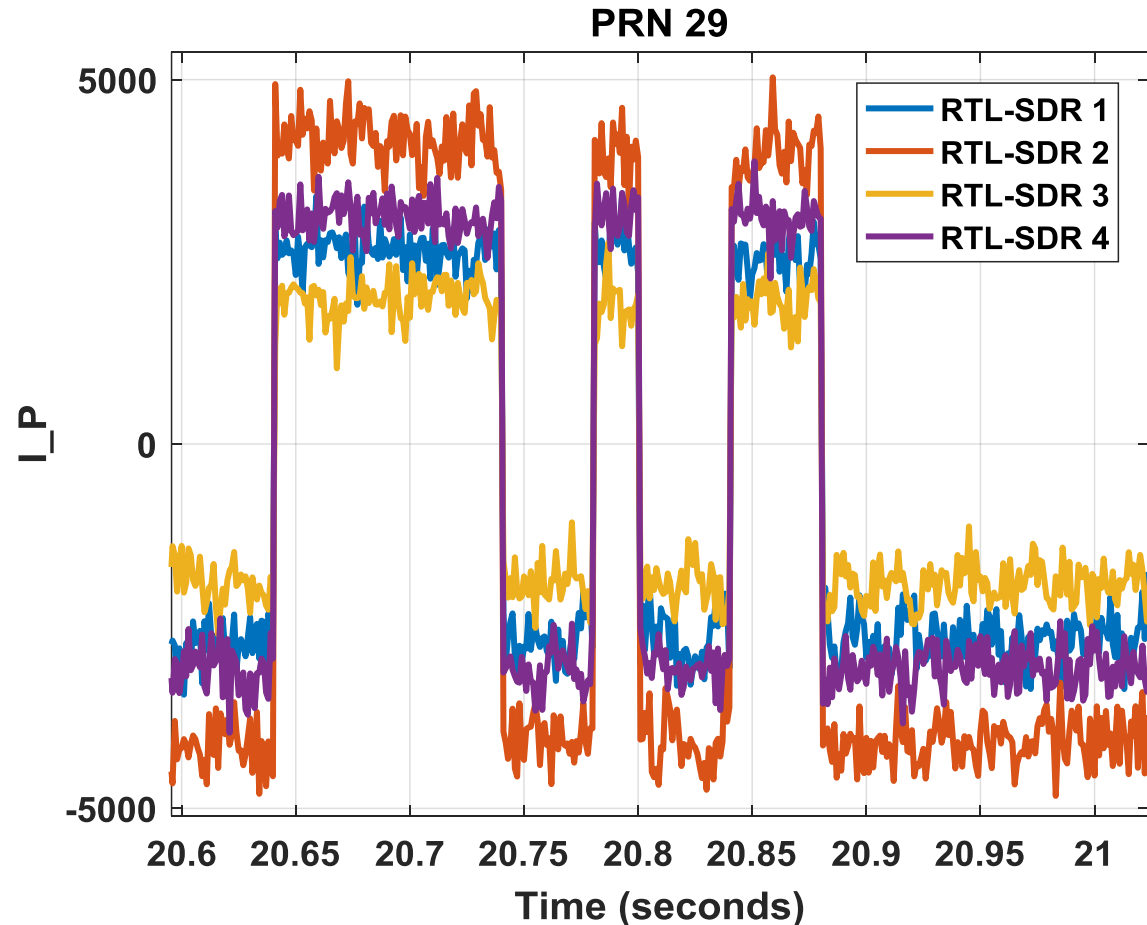
Fine Chip Code  
Synchronization  
based on PRN

Coarse Bit  
Synchronization  
based on PRN

GPS Beamforming  
based on Carrier  
Phase Extraction

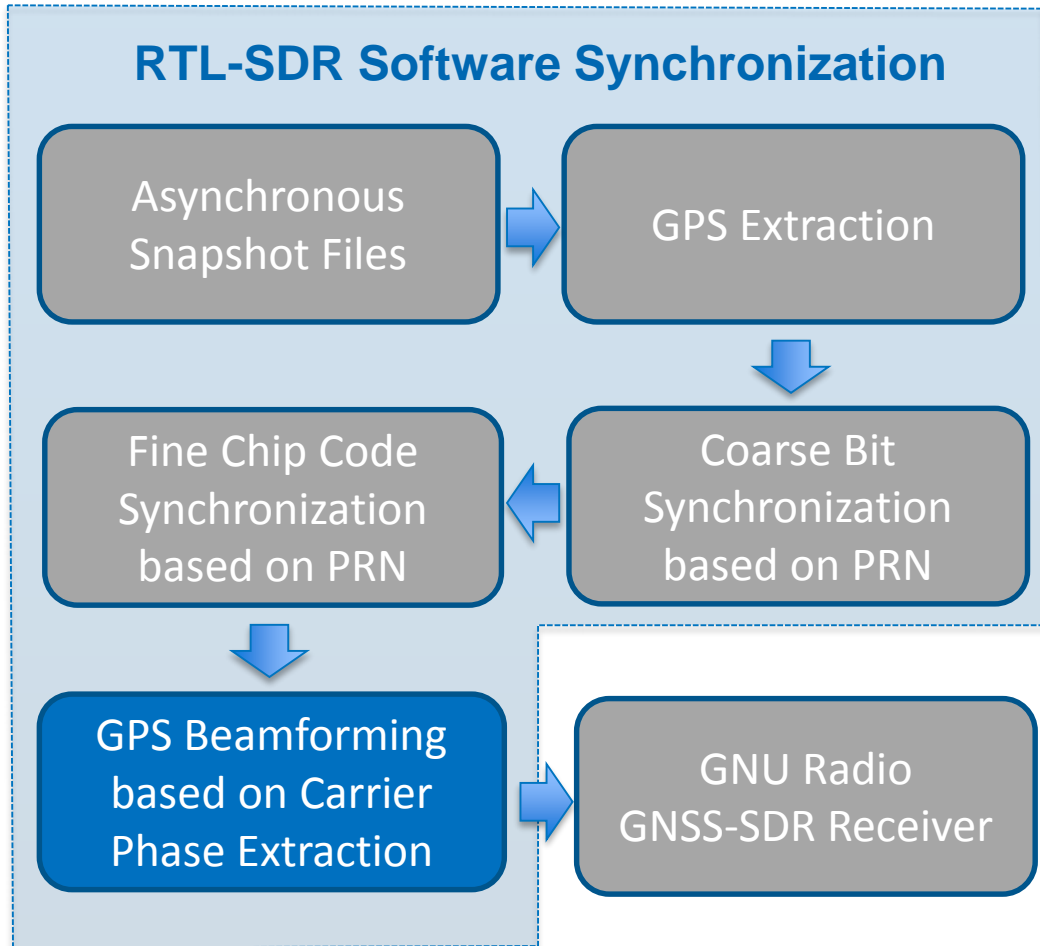
GNU Radio  
GNSS-SDR Receiver

Leverage RTL-SDR 4 as the reference

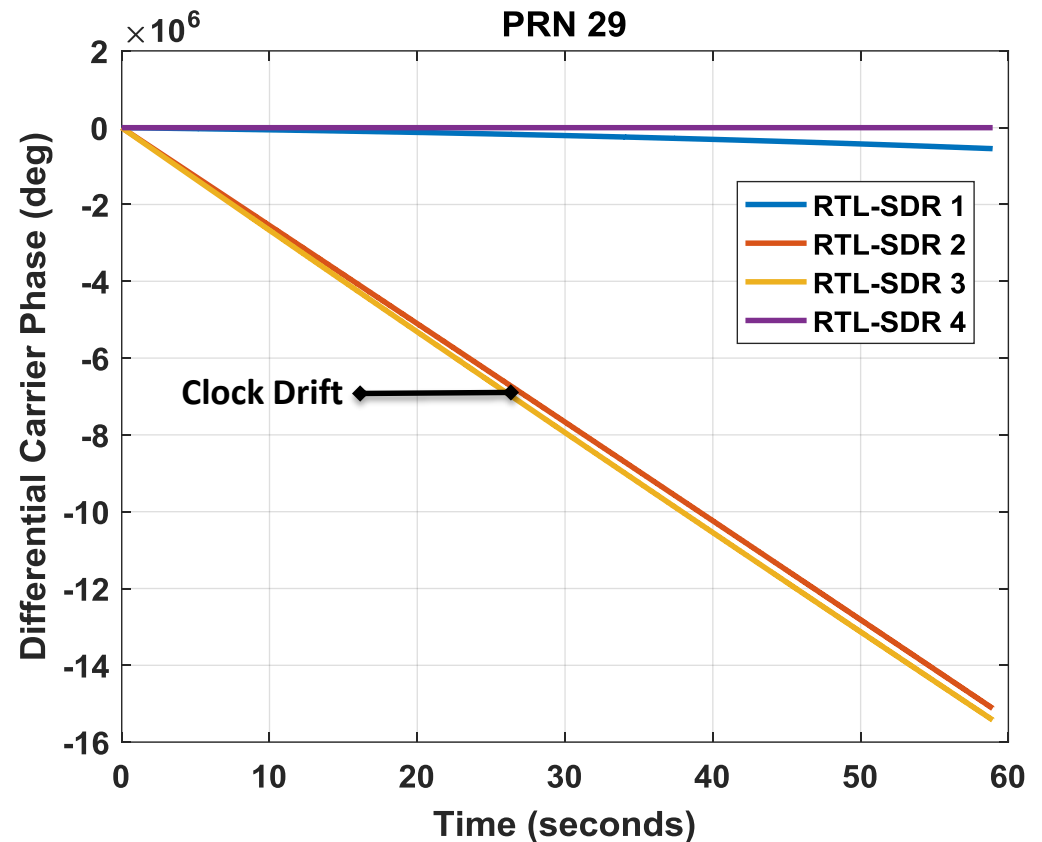




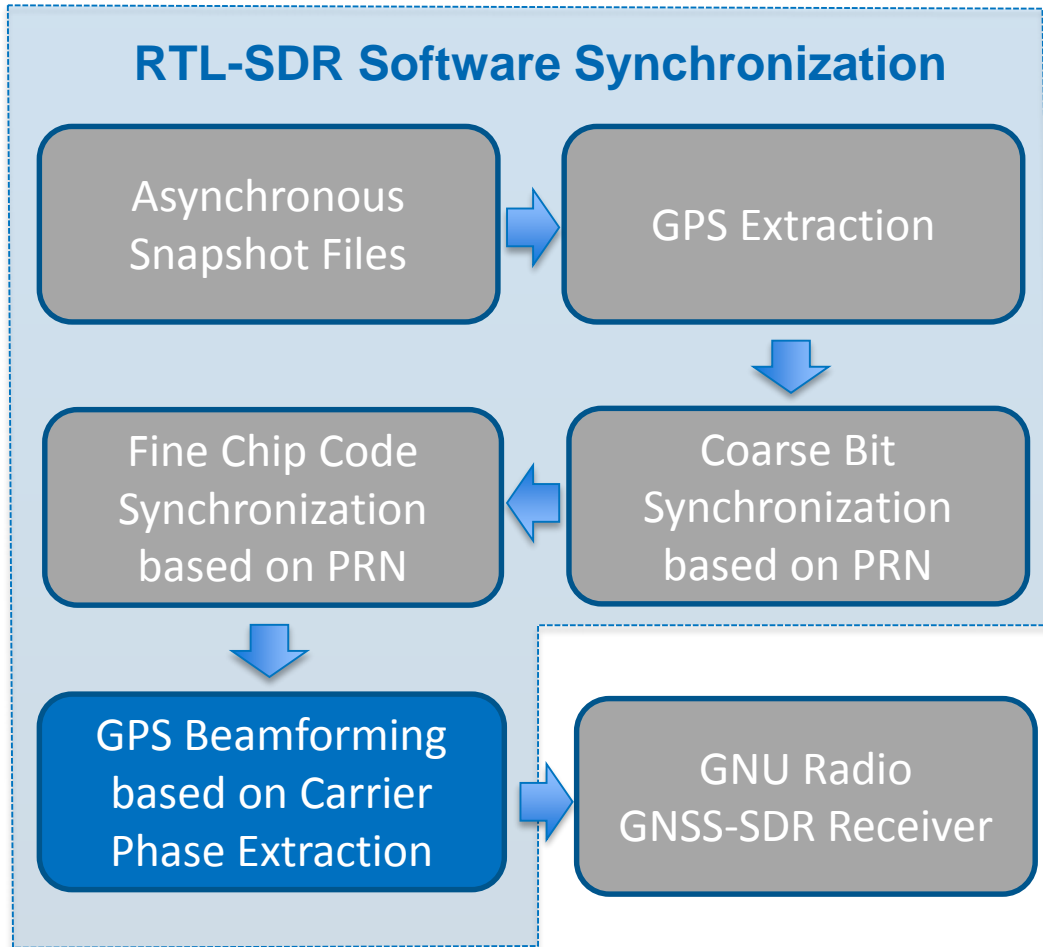
# Carrier Phase Extraction on RTL-SDRs



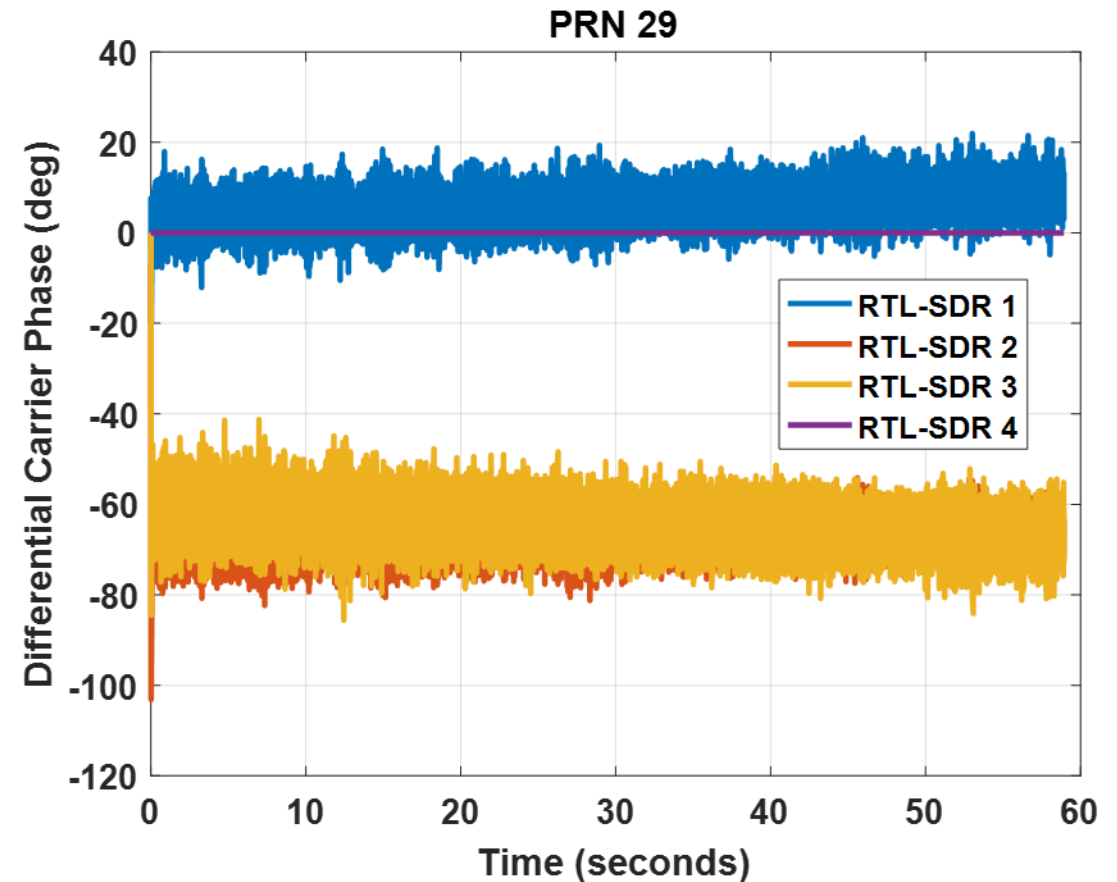
**Differential phase of PRN 29 relative to RTL-SDR 4**



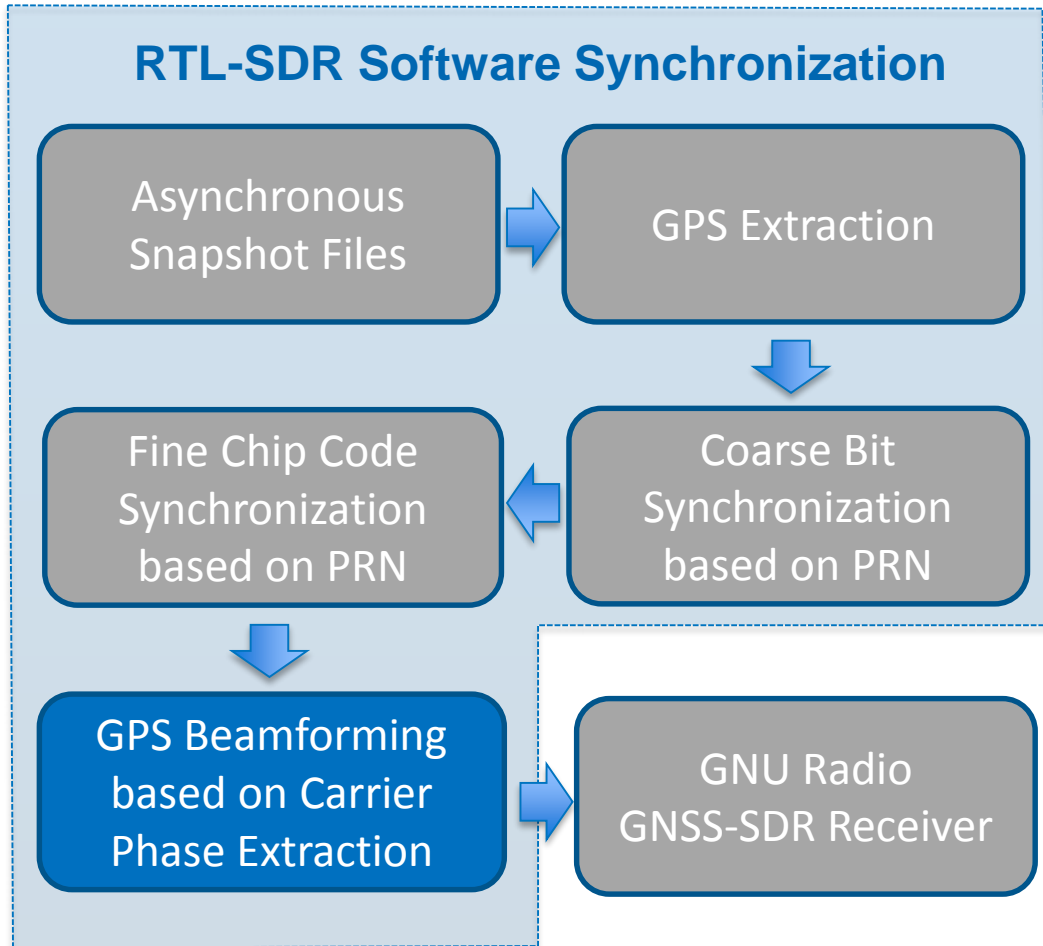
# Carrier Phase Extraction on RTL-SDRs (PRN 29)



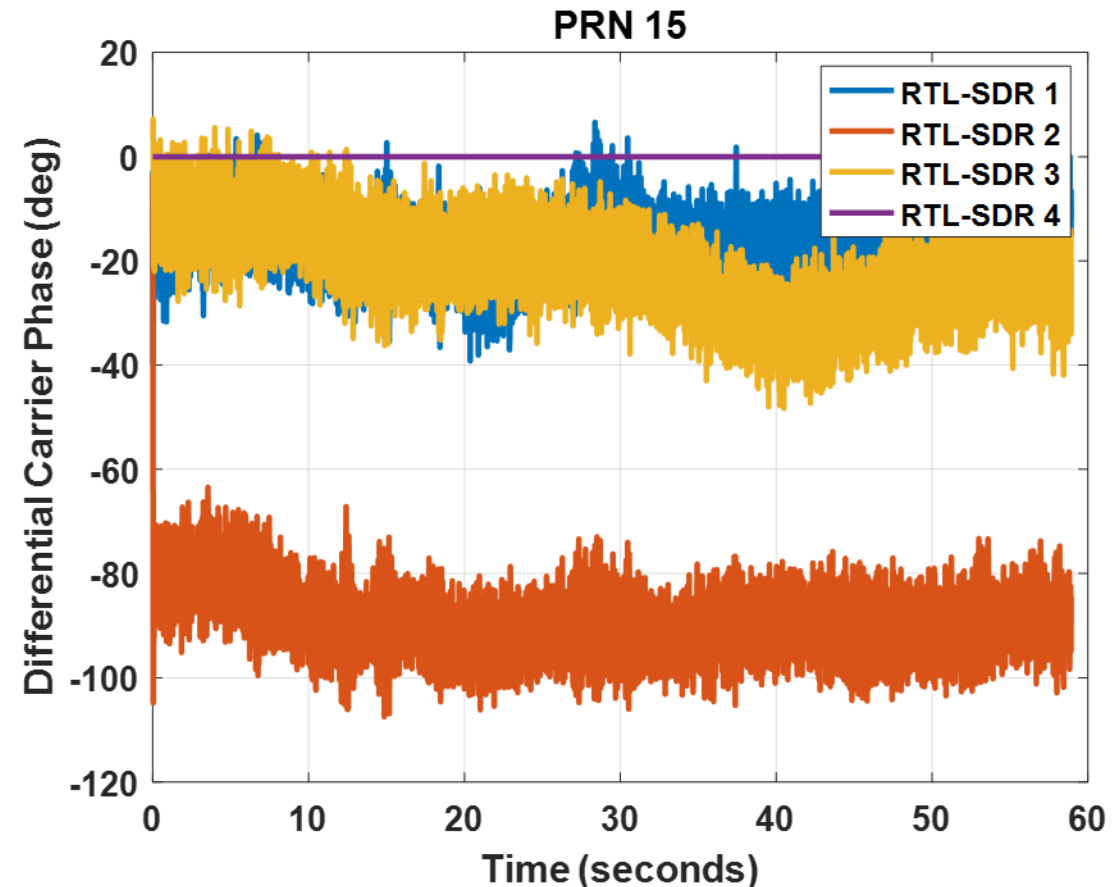
## Differential carrier phase with clock drift compensation



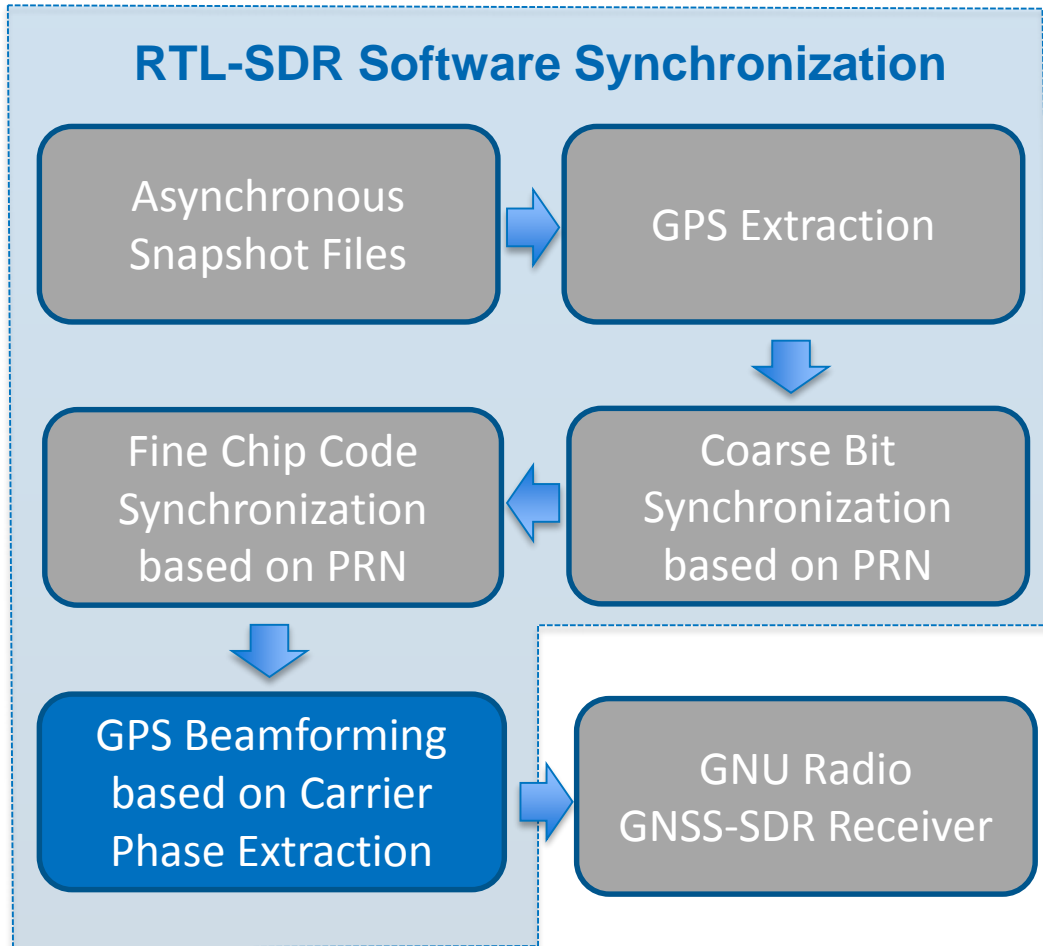
# Carrier Phase Extraction on RTL-SDRs (PRN 15)



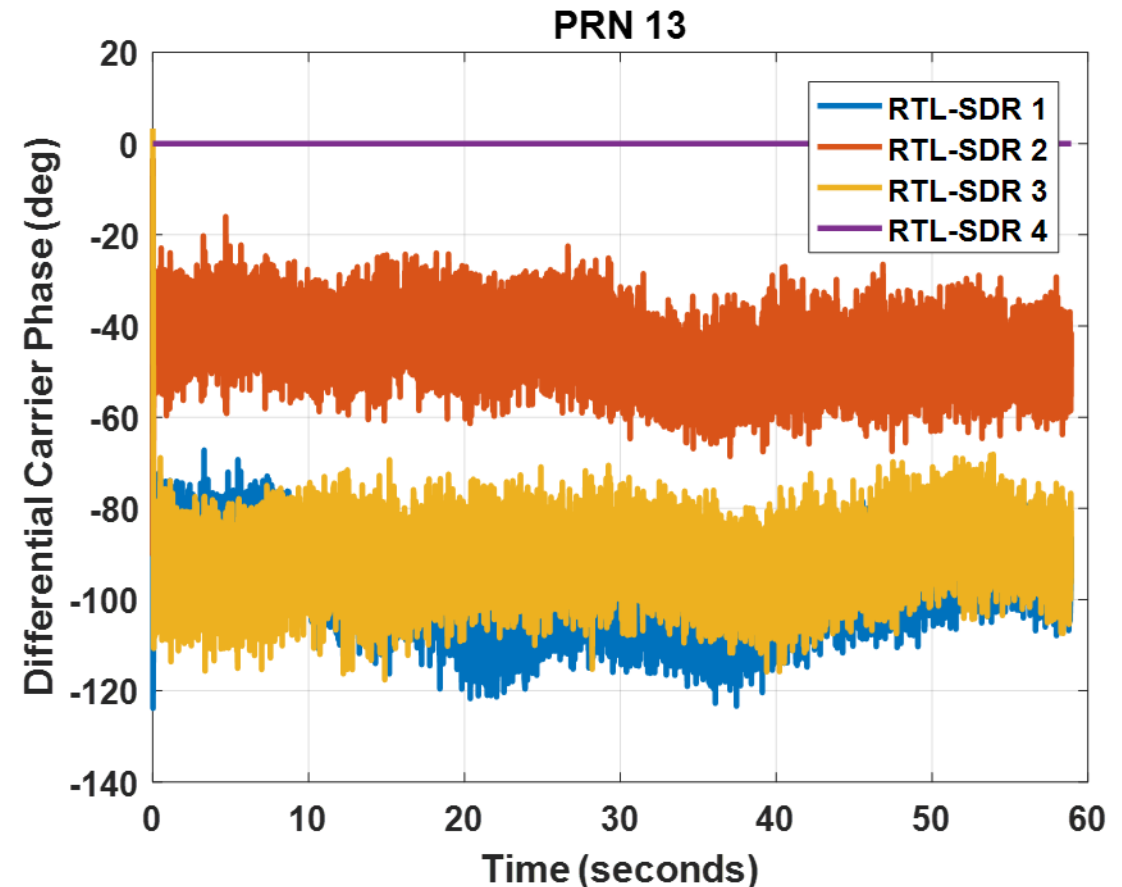
## Differential carrier phase with clock drift compensation



# Carrier Phase Extraction on RTL-SDRs (PRN 13)



## Differential carrier phase with clock drift compensation





# Carrier Phase Extraction on RTL-SDRs (PRN 2)

## RTL-SDR Software Synchronization

Asynchronous  
Snapshot Files



GPS Extraction



Fine Chip Code  
Synchronization  
based on PRN



Coarse Bit  
Synchronization  
based on PRN

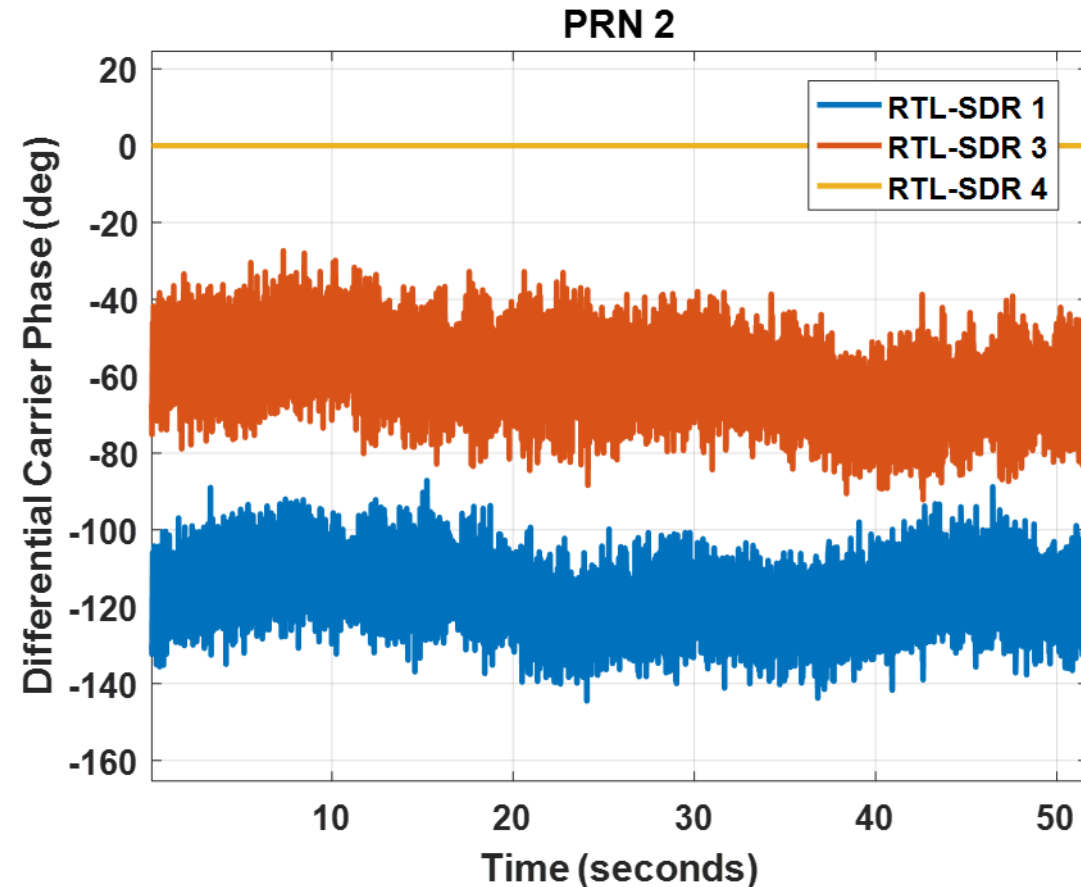


GPS Beamforming  
based on Carrier  
Phase Extraction

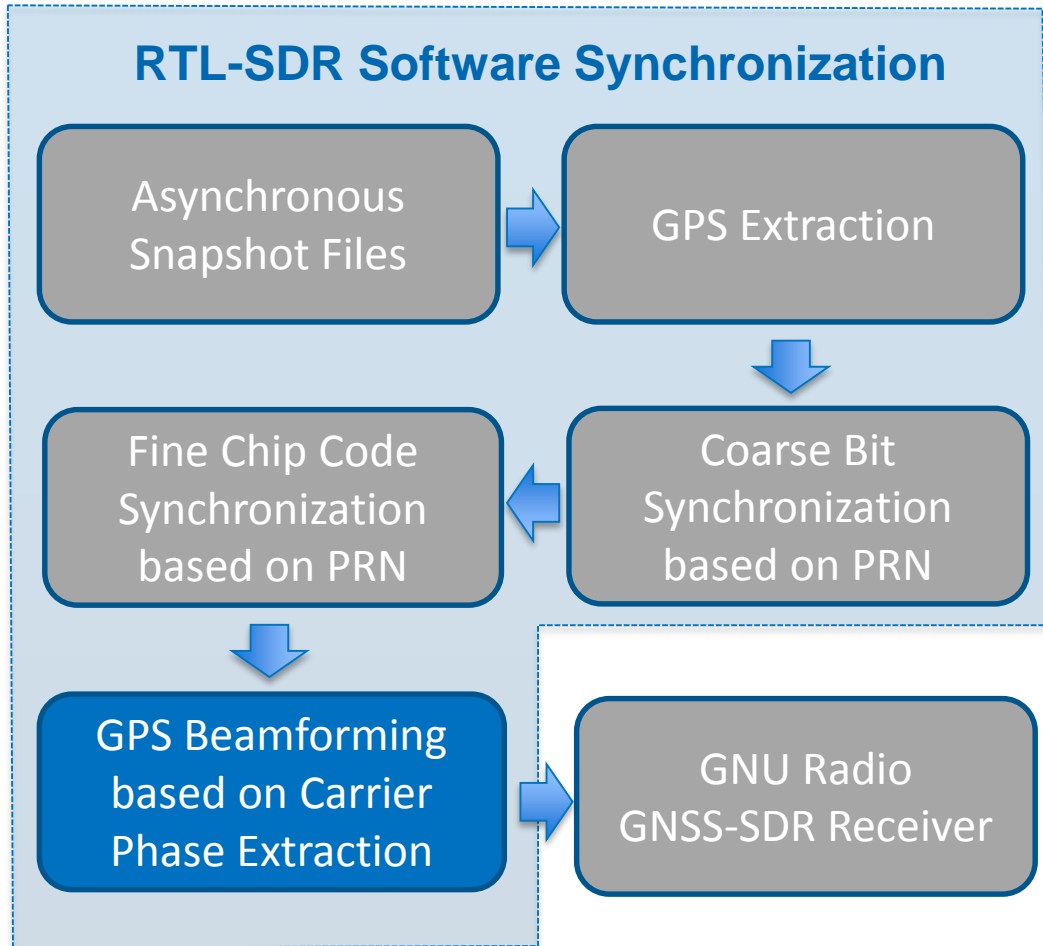


GNU Radio  
GNSS-SDR Receiver

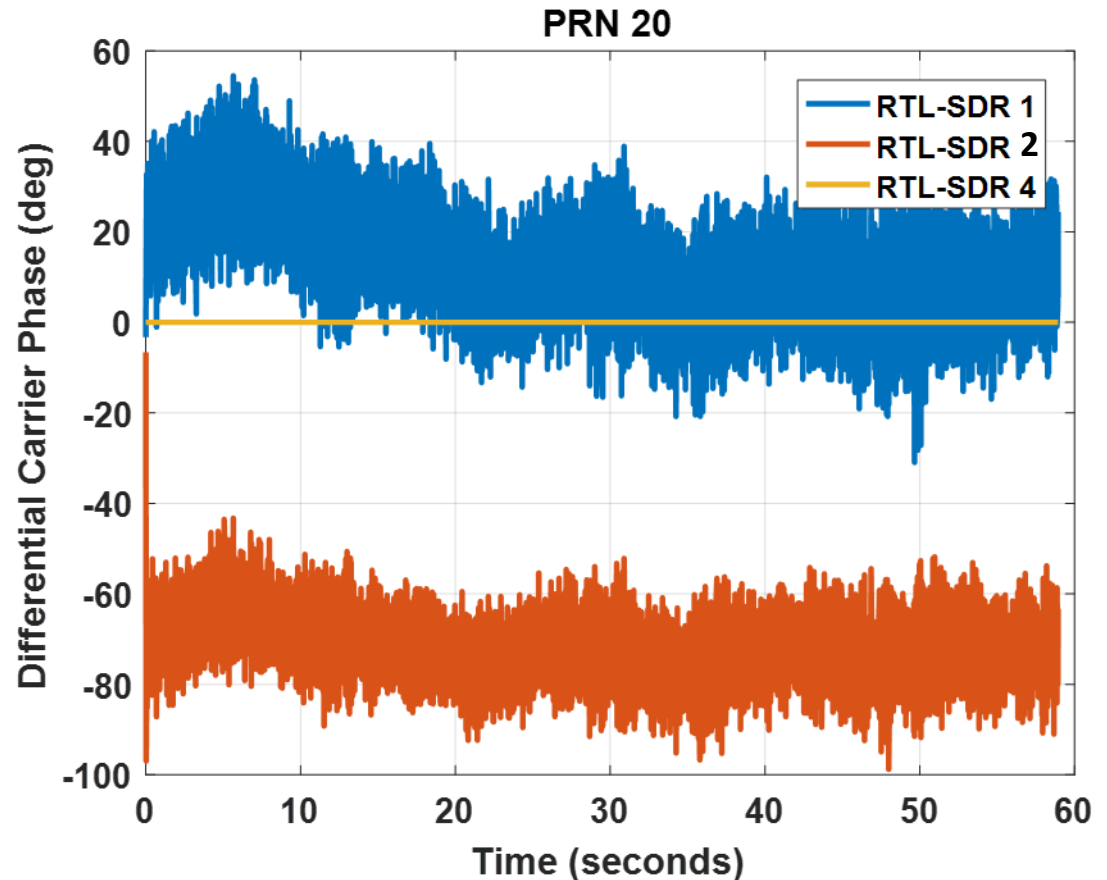
## Differential carrier phase with clock drift compensation



# Carrier Phase Extraction on RTL-SDRs (PRN 20)



## Differential carrier phase with clock drift compensation



# Carrier Phase Extraction on RTL-SDRs (PRN 5)

## RTL-SDR Software Synchronization

Asynchronous  
Snapshot Files

GPS Extraction

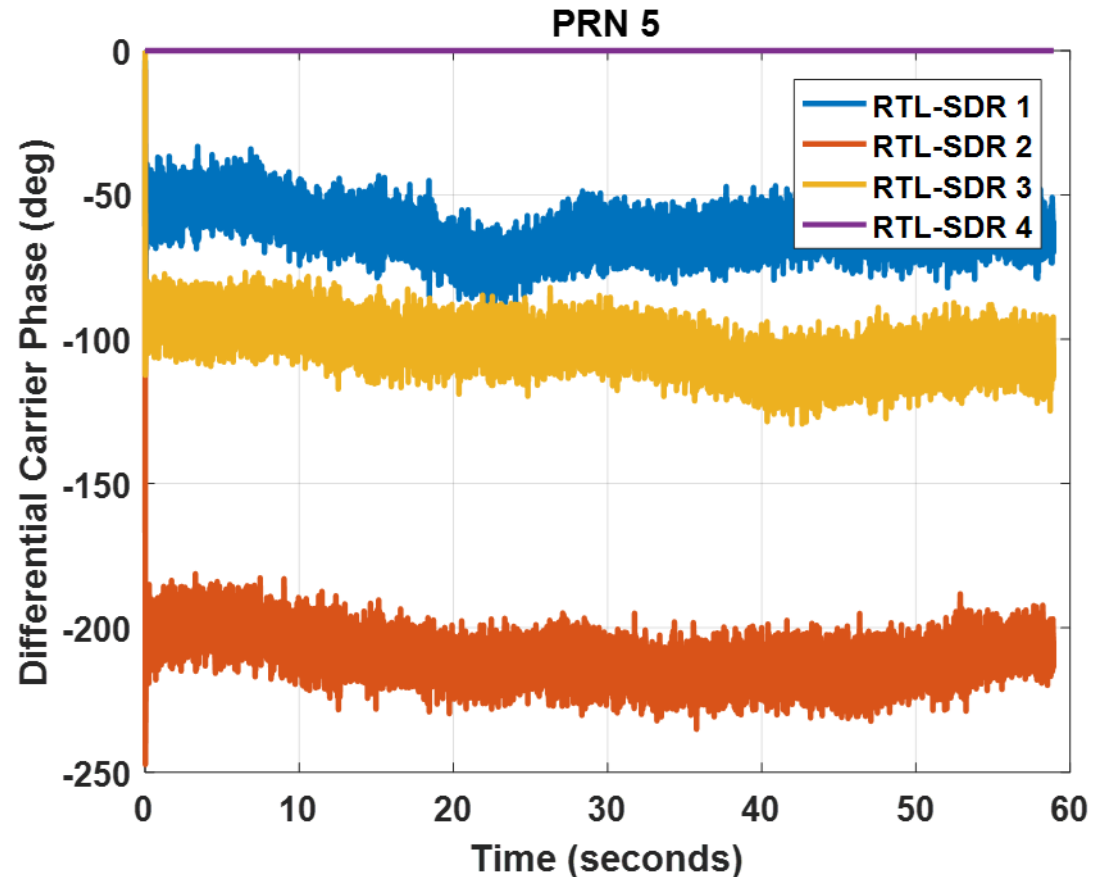
Fine Chip Code  
Synchronization  
based on PRN

Coarse Bit  
Synchronization  
based on PRN

GPS Beamforming  
based on Carrier  
Phase Extraction

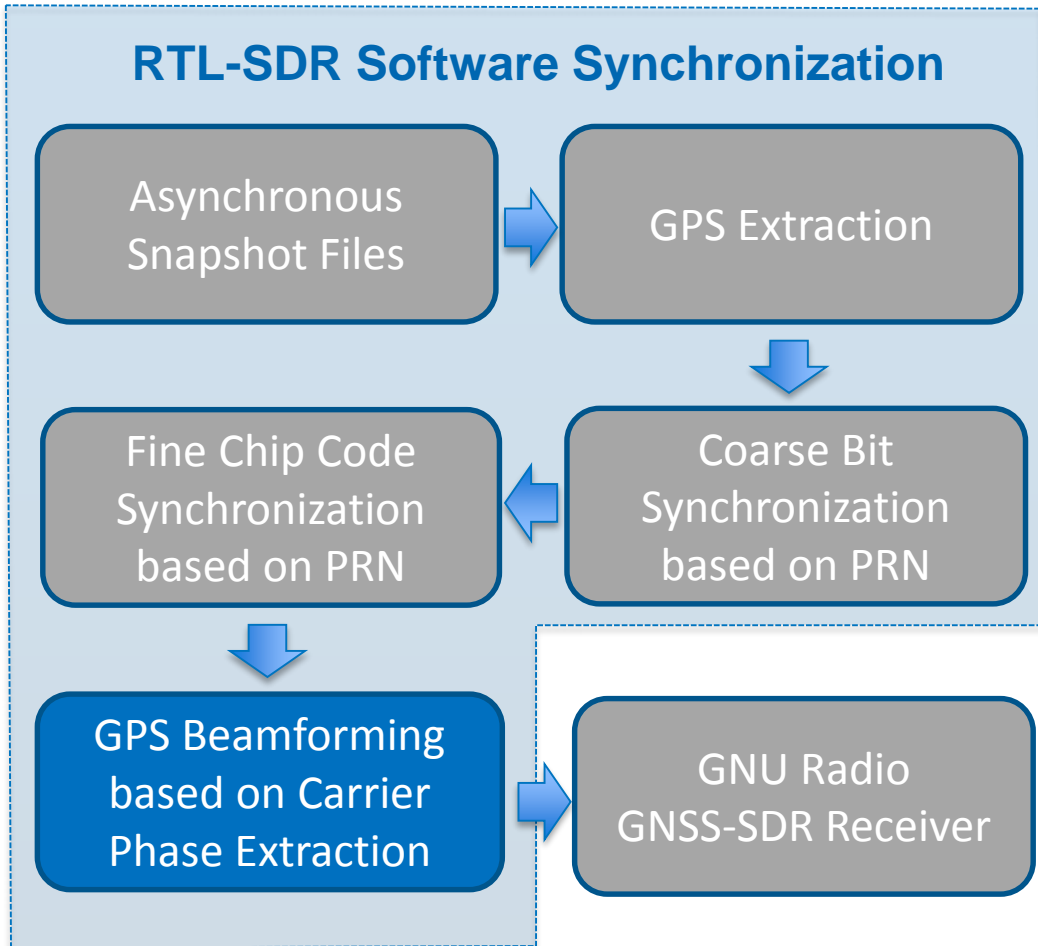
GNU Radio  
GNSS-SDR Receiver

## Differential carrier phase with clock drift compensation



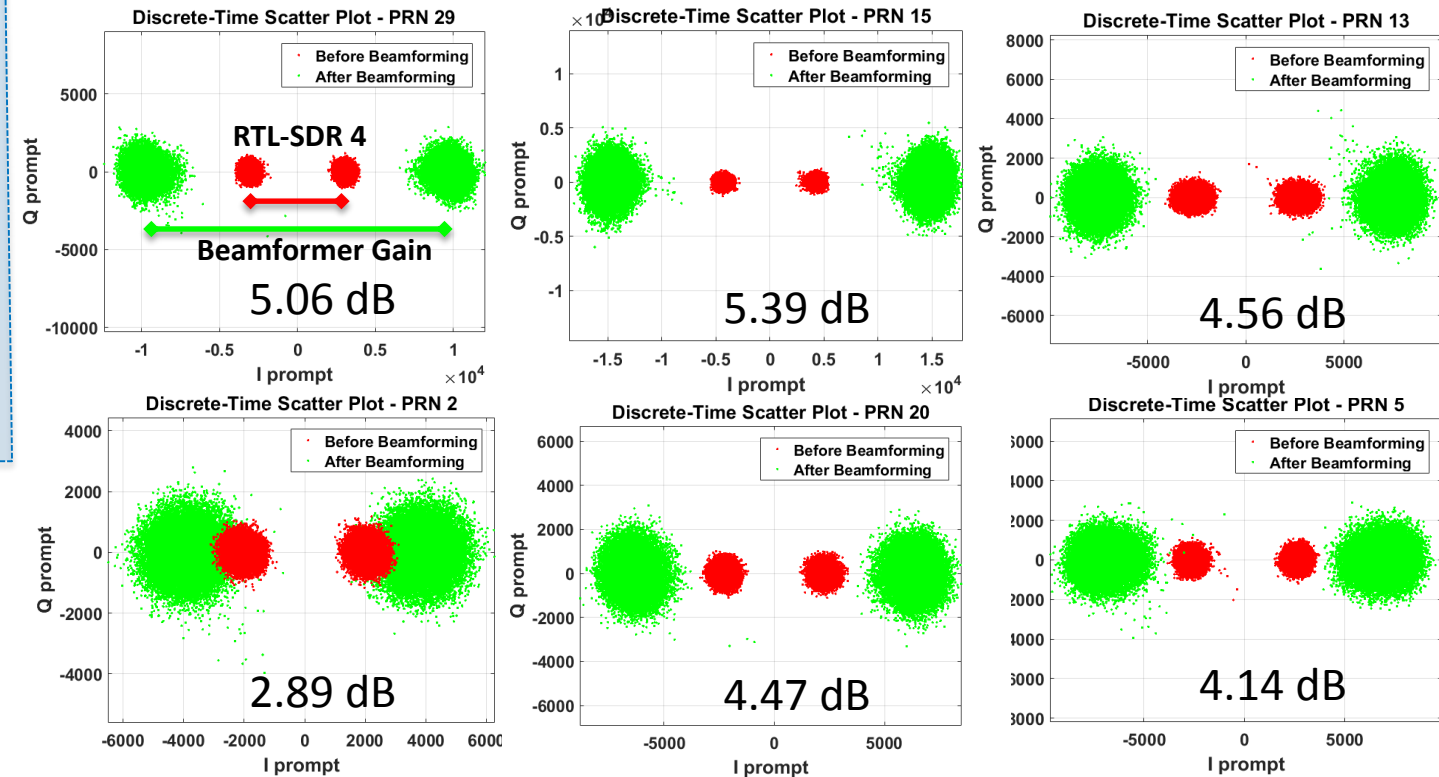
# GPS Beamforming RTL-SDR Performance

## RTL-SDR Software Synchronization



Ideal Gain: ~6dB

## RTL-SDR Beamforming Performance per PRN





# GPS Acquisition across RTL-SDRs

## RTL-SDR Software Synchronization

Asynchronous  
Snapshot Files

GPS Extraction

Fine Chip Code  
Synchronization  
based on PRN

Coarse Bit  
Synchronization  
based on PRN

GPS Beamforming  
based on Carrier  
Phase Extraction

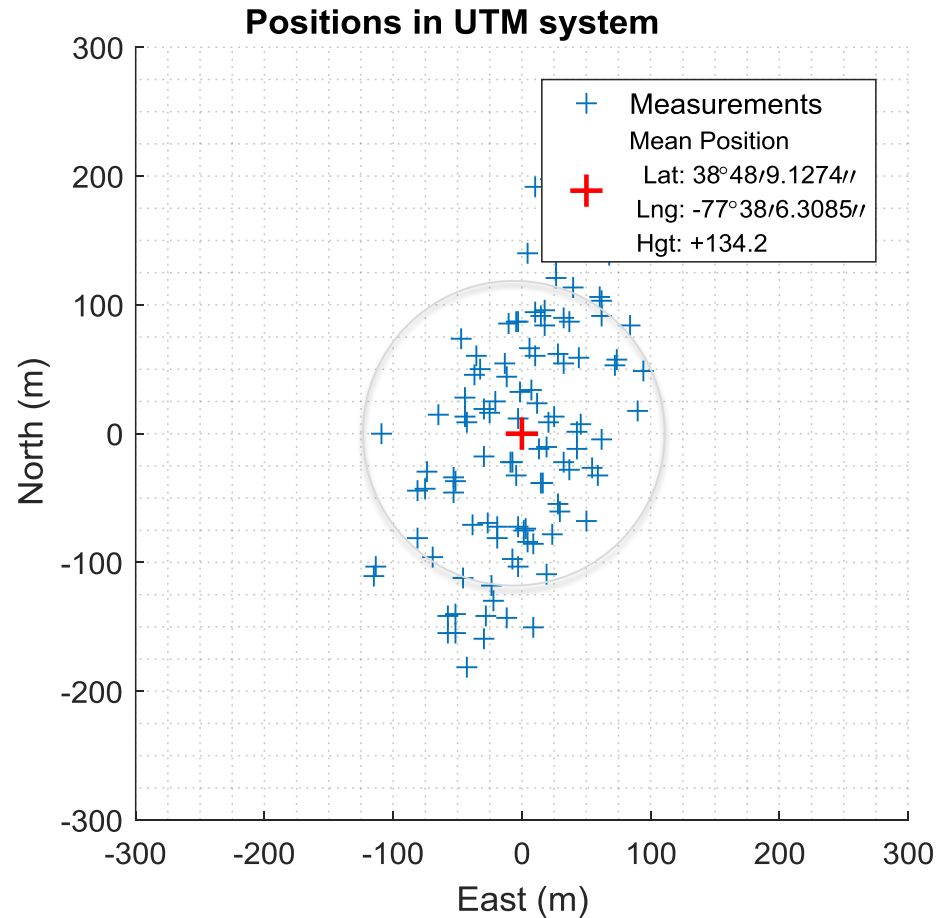
GNU Radio  
GNSS-SDR Receiver

## GNSS-SDR operating on Raspberry Pi 3

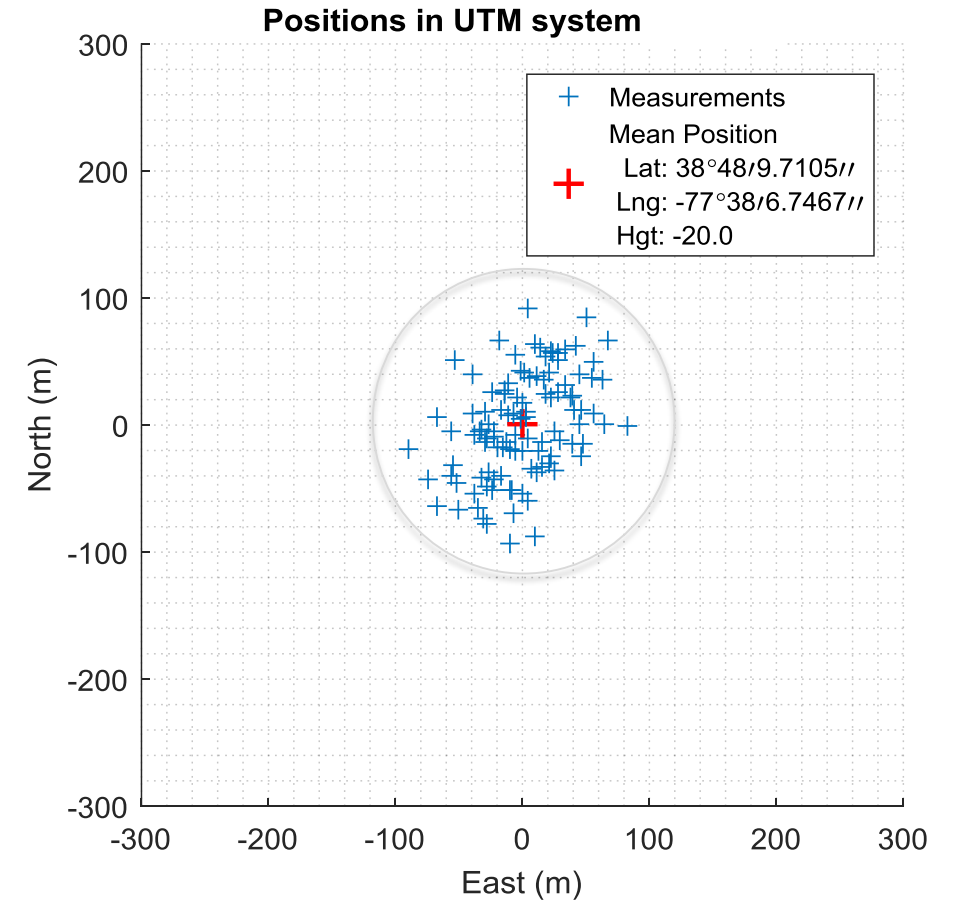
```
myrickw — pi@raspberrypi: ~/Documents — ssh pi@192.168.0.1 — 119x26
Tracking of GPS L1 C/A signal started on channel 1 for satellite GPS PRN 05 (Block IIR-M)
Tracking of GPS L1 C/A signal started on channel 2 for satellite GPS PRN 10 (Block IIF)
Tracking of GPS L1 C/A signal started on channel 3 for satellite GPS PRN 13 (Block IIR)
Tracking of GPS L1 C/A signal started on channel 4 for satellite GPS PRN 15 (Block IIR-M)
Tracking of GPS L1 C/A signal started on channel 5 for satellite GPS PRN 18 (Block IIR)
Tracking of GPS L1 C/A signal started on channel 6 for satellite GPS PRN 20 (Block IIR)
Tracking of GPS L1 C/A signal started on channel 7 for satellite GPS PRN 21 (Block IIR)
Current receiver time: 1 [s]
Loss of lock in channel 0!
Tracking of GPS L1 C/A signal started on channel 0 for satellite GPS PRN 29 (Block IIR-M)
Loss of lock in channel 2!
Loss of lock in channel 5!
Current receiver time: 2 [s]
Loss of lock in channel 7!
Tracking of GPS L1 C/A signal started on channel 2 for satellite GPS PRN 12 (Block IIR-M)
Tracking of GPS L1 C/A signal started on channel 5 for satellite GPS PRN 19 (Block IIR)
Tracking of GPS L1 C/A signal started on channel 7 for satellite GPS PRN 02 (Block IIR)
Current receiver time: 3 [s]
Current receiver time: 4 [s]
Loss of lock in channel 5!
Loss of lock in channel 2!
Current receiver time: 5 [s]
Tracking of GPS L1 C/A signal started on channel 5 for satellite GPS PRN 12 (Block IIR-M)
Tracking of GPS L1 C/A signal started on channel 2 for satellite GPS PRN 18 (Block IIR)
Current receiver time: 6 [s]
```

# RTL-SDR Beamformer Comparison (SDR 2)

## RTL-SDR 2 Only

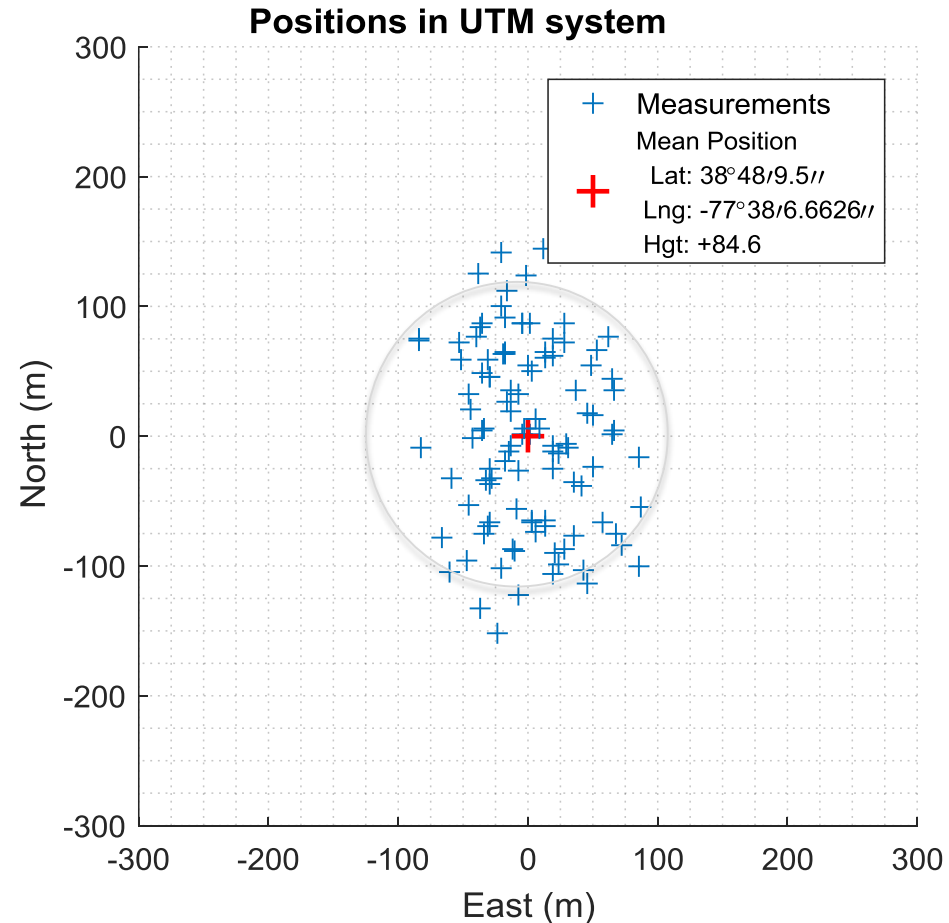


## Best RTL-SDR Beamformer

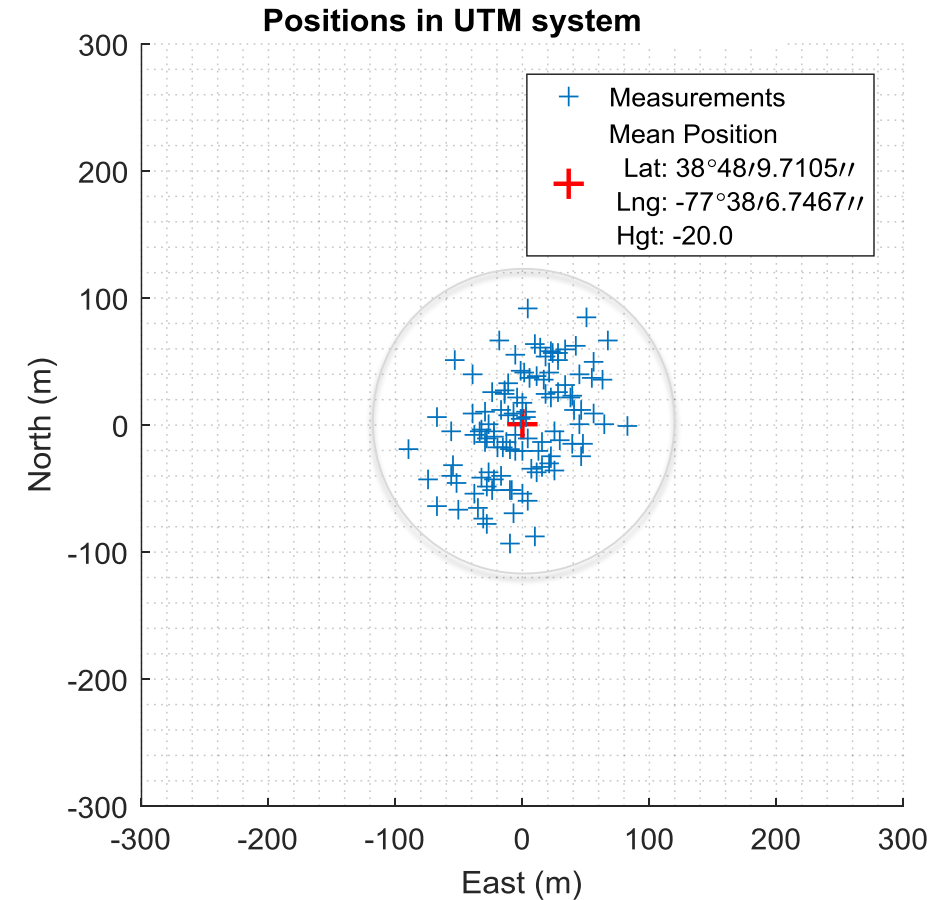


# RTL-SDR Beamformer Comparison (SDR 3)

## RTL-SDR 3 Only

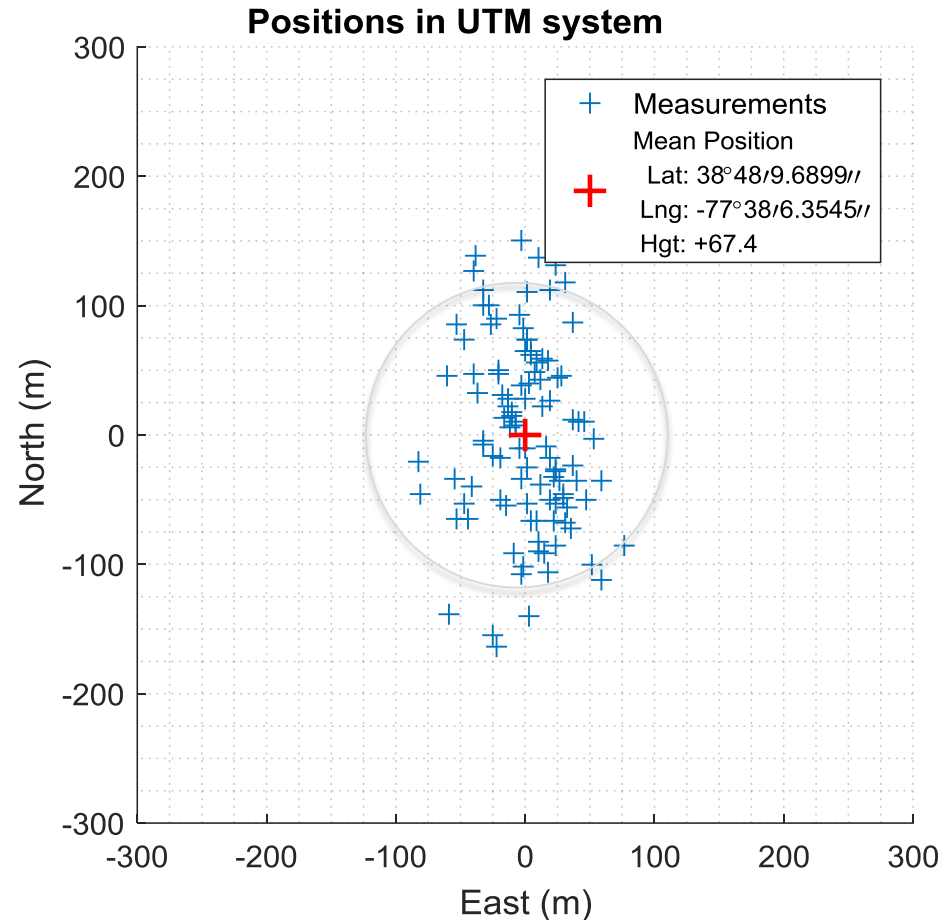


## Best RTL-SDR Beamformer

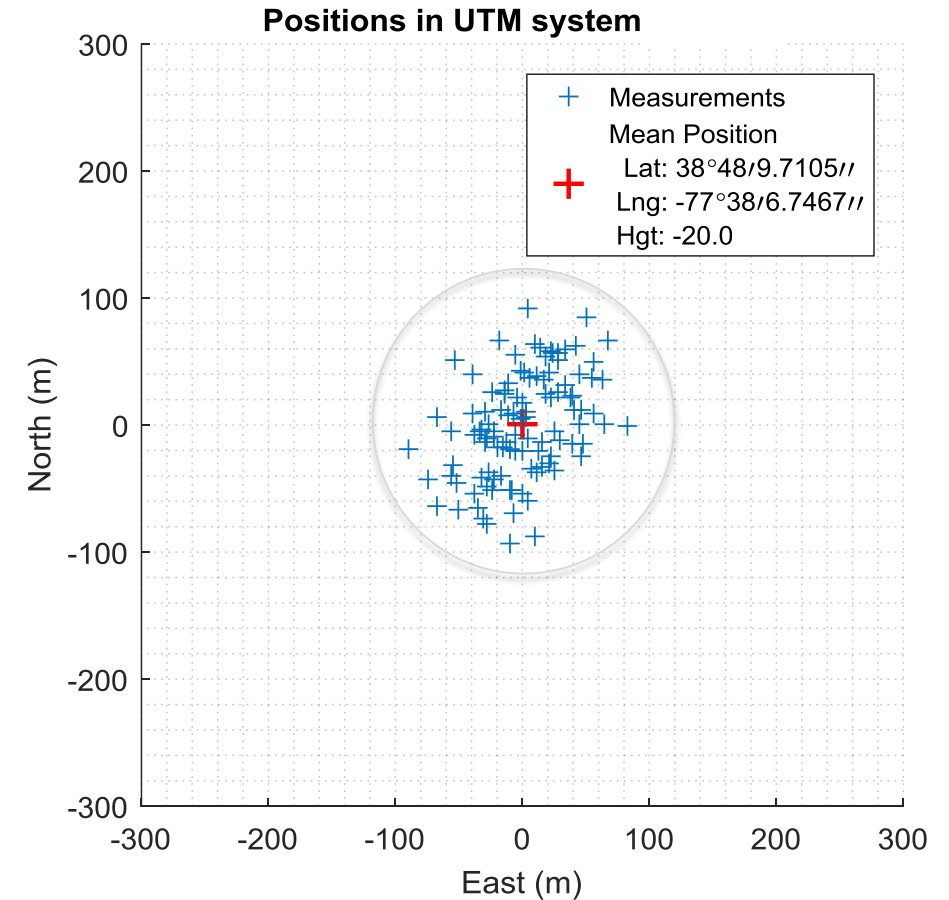


# RTL-SDR Beamformer Comparison (SDR 4)

## RTL-SDR 4 Only



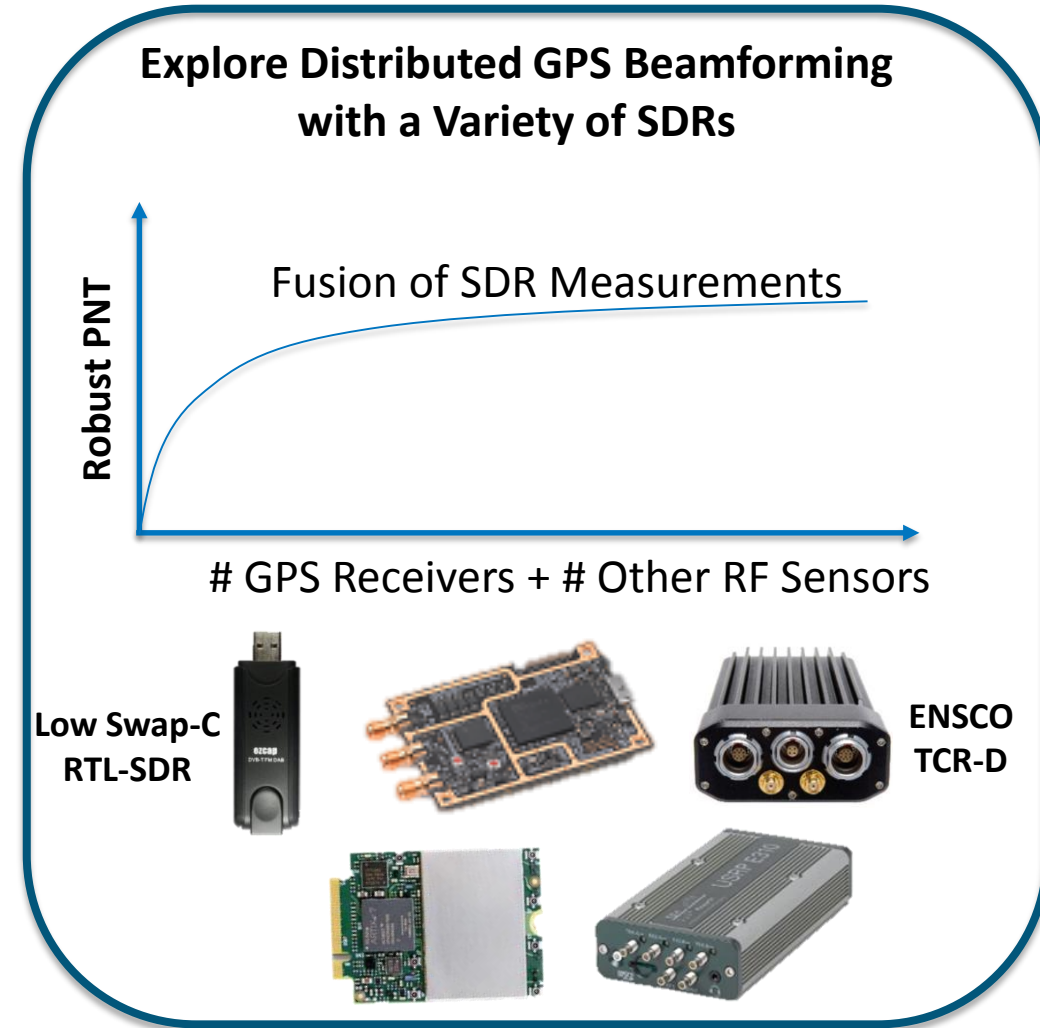
## Best RTL-SDR Beamformer





# Summary and Next Steps

- Initial results show feasibility of GPS beamforming utilizing RTL-SDRs without hardware modification
- “Software Synchronization” preprocessing approach of RTL-SDRs allow exploration of GPS beamforming leveraging existing GNSS-SDR processing architecture
- Plan to explore distributed GPS beamforming with a mixture of SDRs in a variety of environments



# Questions?



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**[myrick.wilbur@ensco.com](mailto:myrick.wilbur@ensco.com)**  
**(703) 321-4504**

**Ideas to Reality™**