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EE290C Final Project: GPS Receiver

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Outline

- Overview
  - Modulation
  - Satellites
- Receiver structure
  - Acquisition
  - Tracking
  - Ranging
- Integration
- Conclusion
  - Next steps

Overview

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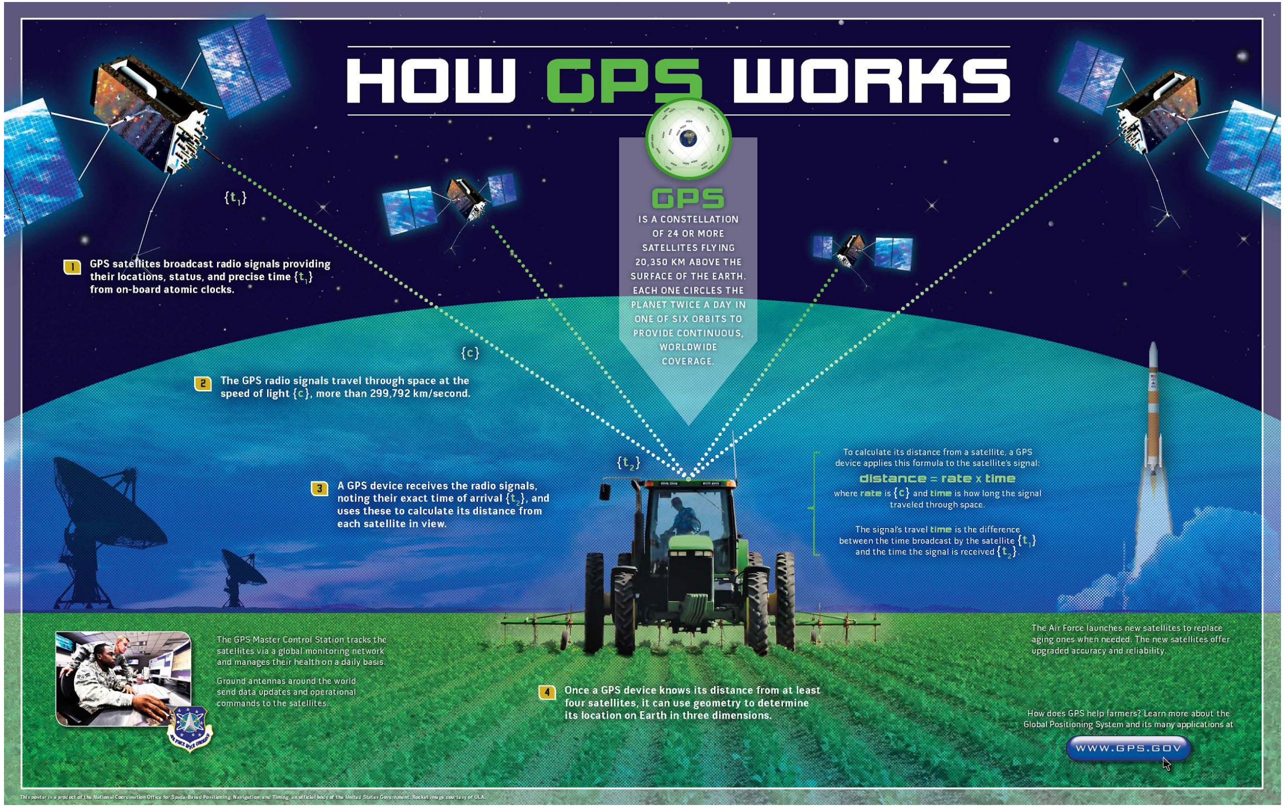
Overview



Source: https://www.af.mil/News/Article-Display/Article/757533/gps-registers-most-accurate-signal-yet/

GPS Signals

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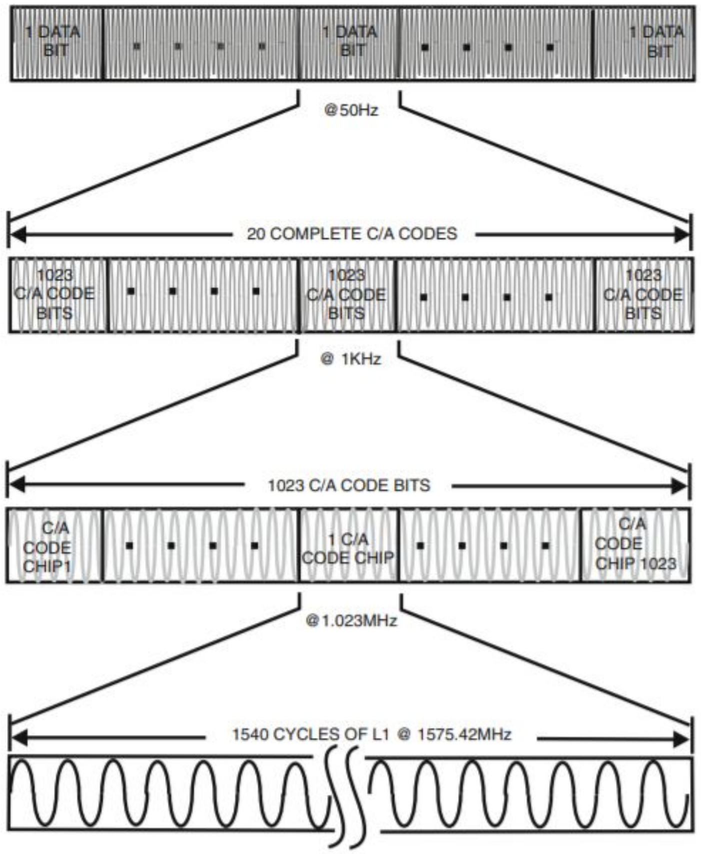
- L1 C/A GPS system
- CDMA scheme
- 1023 length PRN codes
- 50 Hz data
- Info both in message and timing



Doberstein. Fundamentals of GPS Receivers, Springer. 2012.

Acquisition

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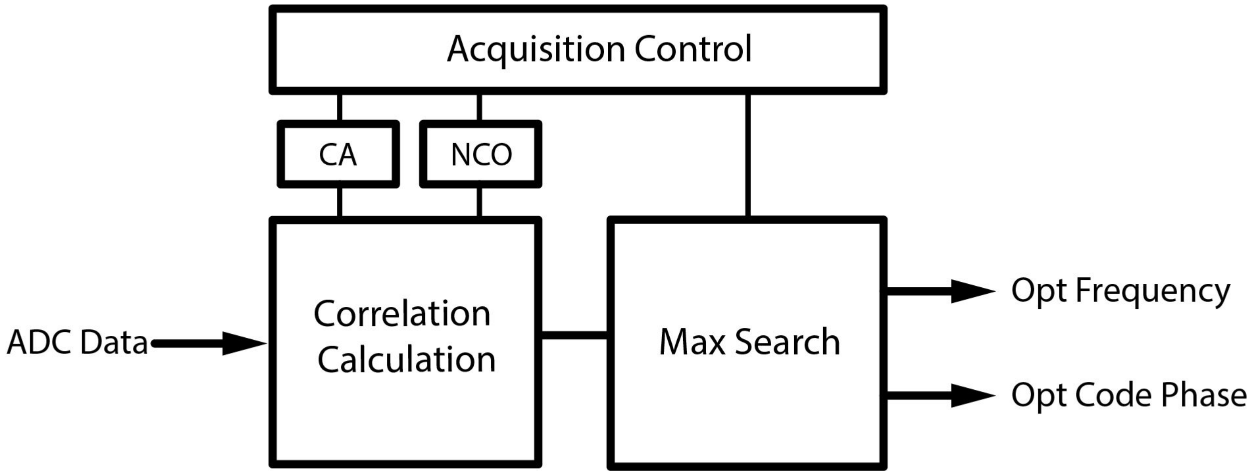
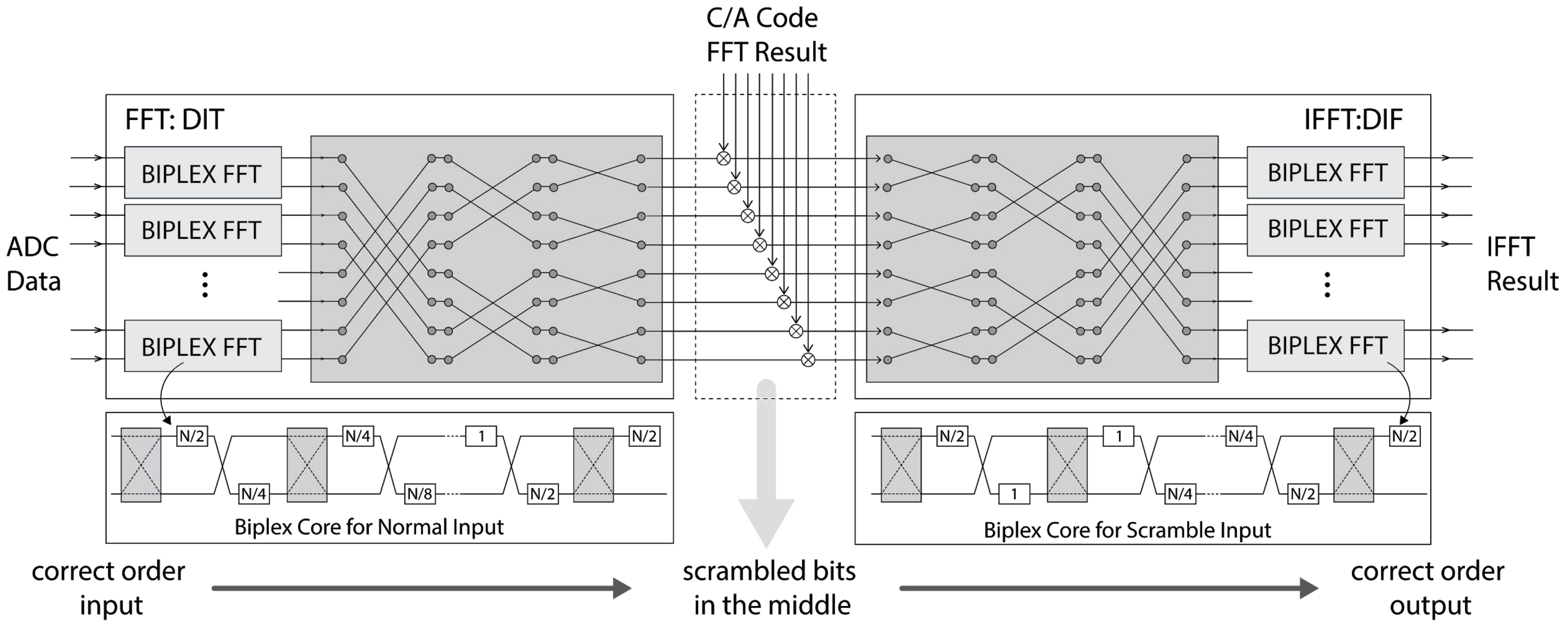
Acquisition: Overview

- Tracking loop has limited frequency and code phase range
  - Need acquisition block to narrow down frequency and code phase
- Get correlation for different frequency and code phase
  - Two methods: FFT and serial correlation calculation



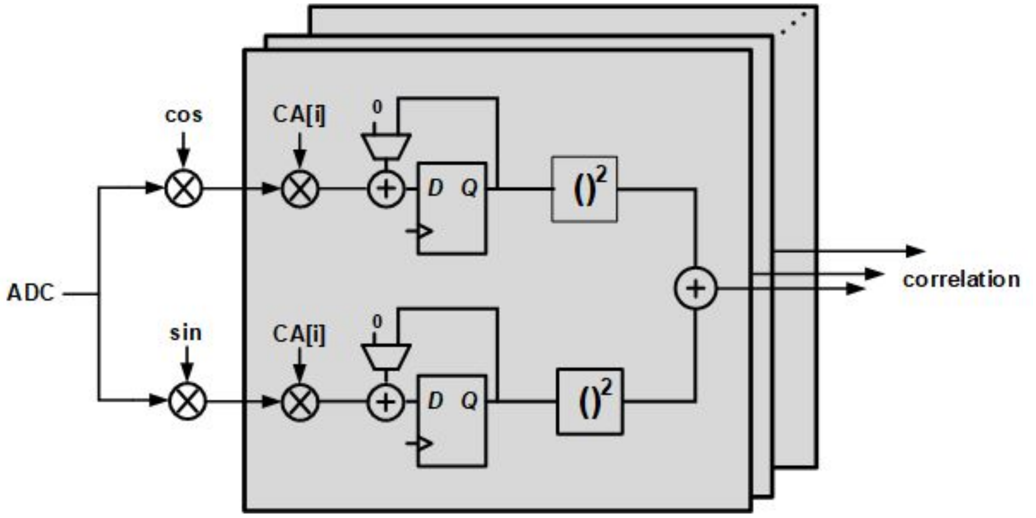
Acquisition: FFT Search



$$R[m] = x[n] \bigotimes CA[-n] = \mathcal{F}^{-1}(\mathcal{F}(x[n]) \cdot \mathcal{F}(CA[n])^*)$$

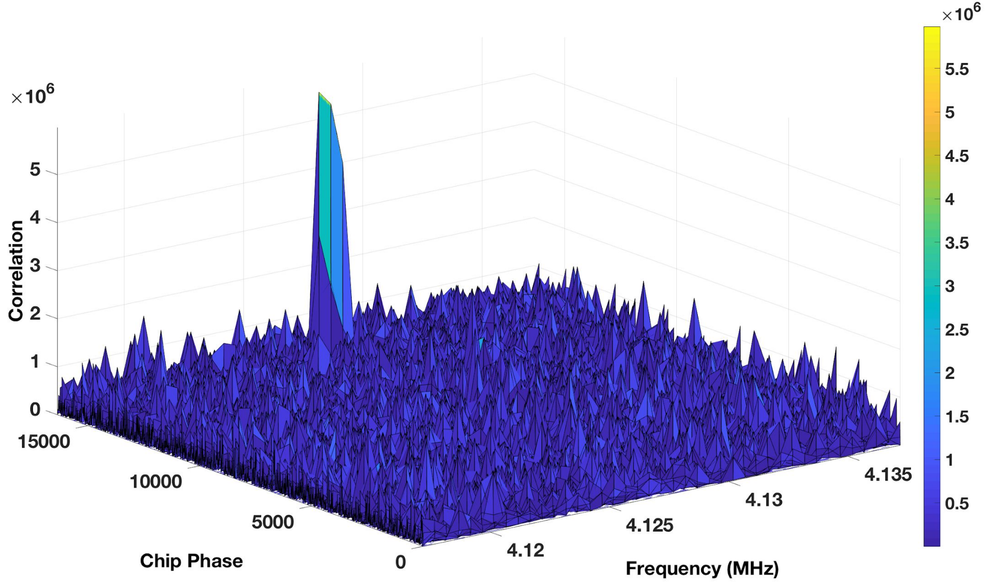
Acquisition: Serial Search

- Correlator: correlation of 1 frequency & code phase
  - Multiple correlators: NCO & ADC signals reuse, acquisition time reduces
  - parallel code phase search, serial frequency search
  - Parameterized number of correlators, number of integration cycles, etc.



Acquisition: Results and Next Steps

- FFT Search takes too much time in compile and simulation, only serial search is verified
- With real GPS data, the optimal frequency and code phase is located successfully
- Both methods are taking much more area than expected, to be solved in future



Results with 40 frequencies with 500Hz frequency steps and 2046 code phases with 8 code phase step

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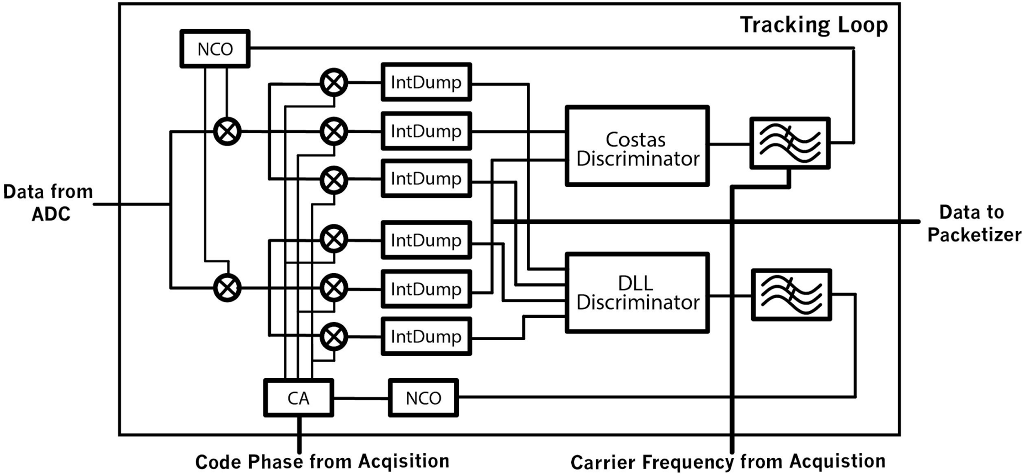
Tracking

Tracking: System Overview

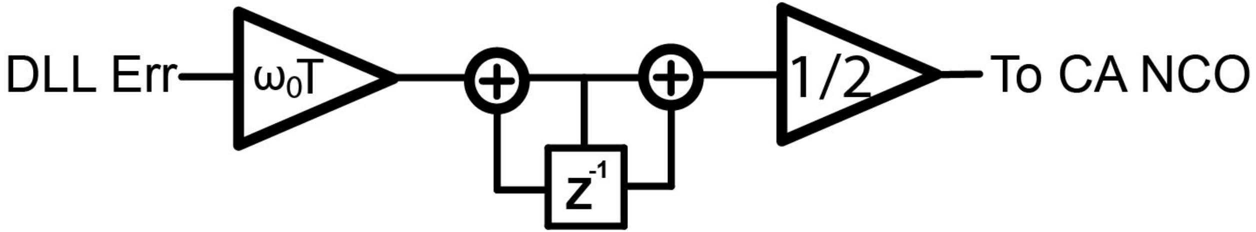
- The tracking loop ensures that the frequency and code phase passed in from the acquisition loop stay locked
  - The code phase lock is maintained using a delay locked loop (DLL)
  - The carrier frequency and phase lock using a frequency assisted Costas loop
- Each loop has a discriminator that turns the correlator outputs into meaningful data and a loop filter that reduces the noise of the discriminator output



Tracking: Code Recovery

- The DLL consists of a discriminator defined by:
  - Normalized early-minus-Late envelope
    - Normalization removes amplitude sensitivity
  - Moderate computational load, no square root calculations
- Also has a first order loop filter that drives the two code generator NCOs:
  - The discrete bilinear transform of a first order analog integrator
  - Unconditionally stable

$$E = I_E^2 + Q_E^2$$
$$L = I_L^2 + Q_L^2$$
$$\Delta\phi_c = \frac{1}{2}\frac{E-L}{E+L}$$

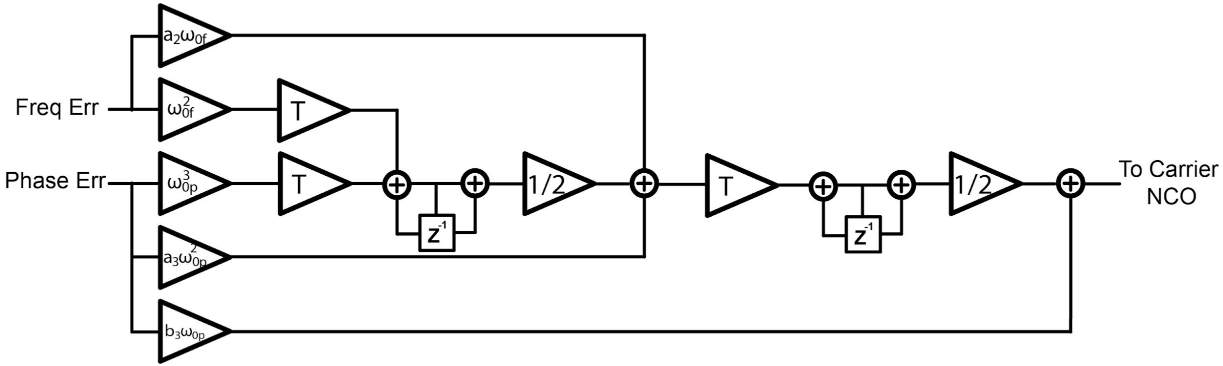


Tracking: Carrier Recovery

- The Costas loop consists of two discriminators:

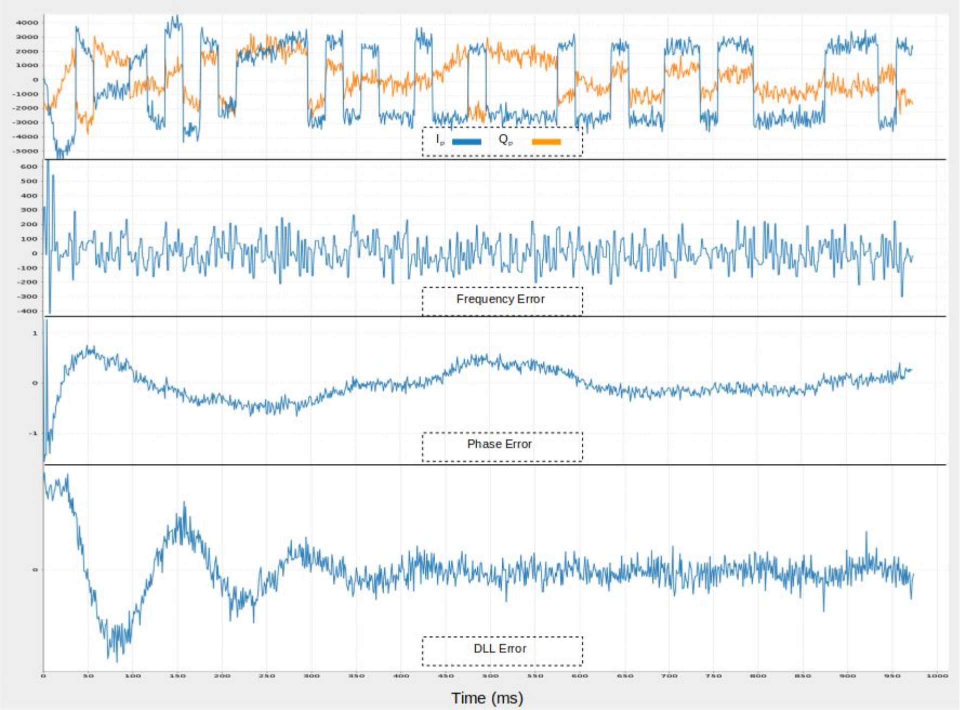
$$\phi_e = \mathrm{ATAN}\left(\frac{Q_p}{I_p}\right) \qquad \omega_e = \frac{\mathrm{ATAN2}\left(Q_p, I_p\right)}{\Delta t}$$

  - A bit transition invariant Costas discriminator using 2 quadrant arctan
  - A bit transition sensitive frequency discriminator using 4 quadrant arctan
    - Added a integrator-based synchronizer to align to bit flips
- The two errors are fed into a 3rd/2nd order filter that drives the carrier NCO



Tracking: Results

- Implemented all the RTL, including CORDICs, for discriminators and loop filters
- Able to track GPS satellites from the example Dataset in a Scala/RTL mixed simulation



Tracking: Next Steps

- Full RTL simulation of Loops does not yet converge due to LSB issues in the CORDICs, need to optimize sizing of Fixed Points
- Current design requires 3 Cordics per tracking channel, need to create a system to “timeshare” a single CORDIC block per channel and loop calculation
- Loop can only do 1ms integration times, need to allow the loop dynamically to dynamically switch to 2, 5, 10 and 20ms integration times
  - Implement a lookup table based coefficient setter for the loop-filters

Ranging

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Ranging Overview

- The ranging code is responsible for the pipeline of hardware decoding to user position. This is the ultimate goal of the GPS receiver.
- Ranging is a three step process:
  - Extract SV parameters and apply scaling/unit conversions
  - Compute “GPS time” and SV position
  - Compute user position

Hardware Extraction - Packetizer

- Bit-domain decoding of data
  - Basic unit of data: 1 word = 30 bits
  - 10 words form a subframe, 5 subframes form a frame
  - Positioning data found in first 3 subframes
- Three submodules in series - parser, parity checker, param extractor

TABLE 5.5 Parity Encoding Equations

$$
\begin{aligned}
d_1 &= D_1 \oplus D_{30}^* \\
d_2 &= D_2 \oplus D_{30}^* \\
d_3 &= D_3 \oplus D_{30}^* \\
&\vdots \\
d_{24} &= D_{24} \oplus D_{30}^* \\
D_{25} &= D_{29}^* \oplus d_1 \oplus d_2 \oplus d_3 \oplus d_5 \oplus d_6 \oplus d_{10} \oplus d_{11} \oplus d_{12} \oplus d_{13} \oplus d_{14} \oplus d_{17} \oplus d_{18} \\
&\quad \oplus d_{20} \oplus d_{23} \\
D_{26} &= D_{30}^* \oplus d_2 \oplus d_3 \oplus d_4 \oplus d_6 \oplus d_7 \oplus d_{11} \oplus d_{12} \oplus d_{13} \oplus d_{14} \oplus d_{15} \oplus d_{18} \oplus d_{19} \\
&\quad \oplus d_{21} \oplus d_{24} \\
D_{27} &= D_{29}^* \oplus d_1 \oplus d_3 \oplus d_4 \oplus d_5 \oplus d_7 \oplus d_8 \oplus d_{12} \oplus d_{13} \oplus d_{14} \oplus d_{15} \oplus d_{16} \oplus d_{19} \\
&\quad \oplus d_{20} \oplus d_{22} \\
D_{28} &= D_{30}^* \oplus d_2 \oplus d_4 \oplus d_5 \oplus d_6 \oplus d_8 \oplus d_9 \oplus d_{13} \oplus d_{14} \oplus d_{15} \oplus d_{16} \oplus d_{17} \oplus d_{20} \\
&\quad \oplus d_{21} \oplus d_{23} \\
D_{29} &= D_{30}^* \oplus d_1 \oplus d_3 \oplus d_5 \oplus d_6 \oplus d_7 \oplus d_9 \oplus d_{10} \oplus d_{14} \oplus d_{15} \oplus d_{16} \oplus d_{17} \oplus d_{18} \\
&\quad \oplus d_{21} \oplus d_{22} \oplus d_{24} \\
D_{30} &= D_{29}^* \oplus d_3 \oplus d_5 \oplus d_6 \oplus d_8 \oplus d_9 \oplus d_{10} \oplus d_{11} \oplus d_{13} \oplus d_{15} \oplus d_{19} \oplus d_{22} \\
&\quad \oplus d_{23} \oplus d_{24}
\end{aligned}
$$

Parity check equations (*Fundamentals of Global Positioning System Receivers: A Hardware Approach*)

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Hardware Extraction - Packetizer (cont.)

- Parser
  - Detects 8-bit GPS preamble that indicates the start of a subframe
  - Reads 300 bits into a buffer and passes to next stage
- Parity checker
  - Each word has 24 data bits and 6 parity bits
  - Parity bits are calculated with certain XOR patterns of the 24 data bits and the 2 last bits of the previous word
  - Parity check must pass on all words of a subframe for data to be valid
- Param extractor
  - Identifies subframe and extracts relevant parameters for ranging algorithm
  - This submodule was added later, as the bit manipulations it requires were inefficient in software

Hardware Extraction - Packetizer (cont.)

- Firmware-hardware interfacing done through a regmap
  - Read UInts/SInts from Chisel, convert data types and apply scaling in hardware
  - Package as a struct to be passed to ranging algorithm
- Different memory block per tracking channel

SV Position Calculation

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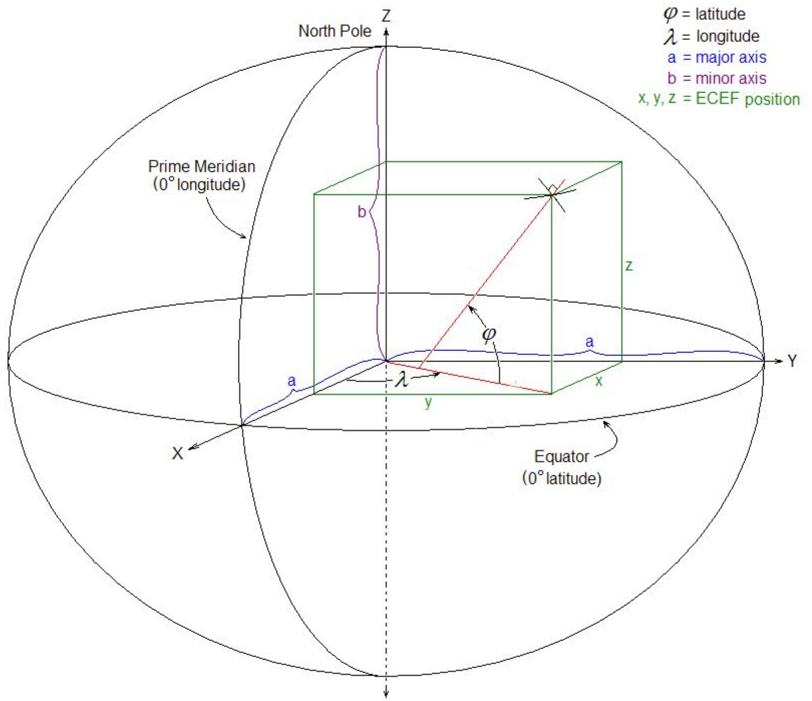
- “GPS time” is a local replica of the SV clock
- SV ephemeris data contains info necessary to compute this time delay
- SV Position is computed using an established set of equations that include correction for motion and other non-idealities



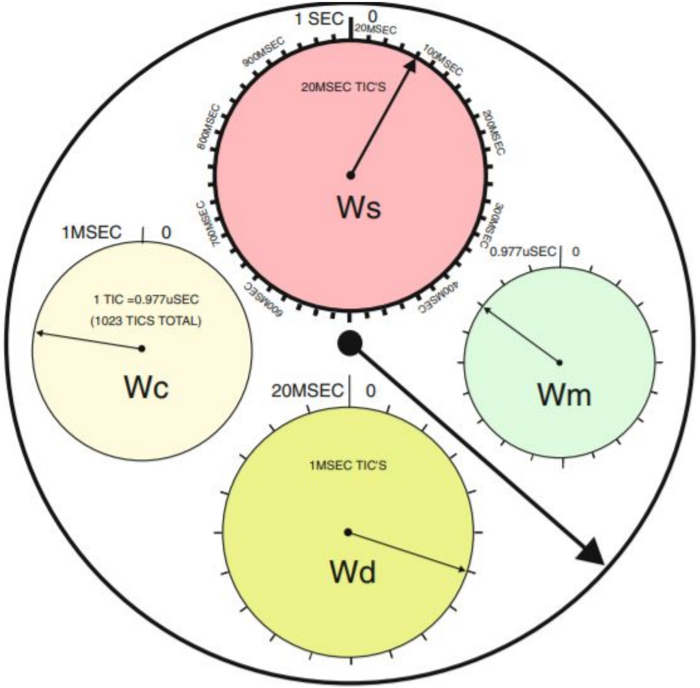
ECEF (Earth-Centered, Earth-Fixed) Coordinates
Image source: https://en.wikipedia.org/wiki/ECEF

SV Position Calculation (Cont.)

- After parameter extraction, local replica clock is created and SV position is computed
- These results are stored in a struct
- After four sets of SV data are populated, they are sent to the user position calculation

Receiver Position Calculation

- Inputs:
  - 4 SV Positions
  - Signal transmit and receive times
- Outputs:
  - Receiver position
  - Receiver time bias
- Tracking loop is a model of the SV signal at transmit
- Pseudorange
- Iterative calculation



Doberstein. Fundamentals of GPS Receivers, Springer. 2012.

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Ranging Conclusion and Next Steps

- The skeleton for computation is complete, but is not fully integrated with hardware due to incomplete datapath
- Using decoded data from jks.com/gps/gps.html we were able to verify that the SV position calculation is correct
- Decoding parameters and recording times from tracking loop measurements

BWRC Location (km):

- X: -2691.466
- Y: -4262.826
- Z: 3894.033

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Integration

Integration: Results and Next Steps

- The tracking channel has been connected to Rocket using a register mapped approach

Next Steps:

- The next integration component is to connect the acquisition loop with the tracking loop
  - The current plan is to connect the two using RocketChip
  - Cannot be done until after the acquisition area has been optimized
- Ranging code also needs to be tested with the tracking loop hardware and Rocket

Documentation

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Scala Docs

gps

package **gps**

Filter all members

Type Members

```
class ACtrl[T <: Data]
class ACtrlAInputBundle[T <: Data]
class ACtrlAOutputBundle[T <: Data]
class ACtrlDebugBundle[T <: Data]
class ACtrlIO[T <: Data]
trait ACtrlParams[T <: Data]
class ACtrlTInputBundle[T <: Data]
class ACtrlTOutputBundle[T <: Data]
class ALoop[T1 <: Data, T2 <: Data]
class ALoopDebugBundle[T1 <: Data, T2 <: Data]
class ALoopIO[T1 <: Data, T2 <: Data]
class ALoopInputBundle[T1 <: Data, T2 <: Data]
```

Packages

root

gps

- ACtrl
- ACtrlAInputBundle
- ACtrlAOutputBundle
- ACtrlApp
- ACtrlDebugBundle
- ACtrlIO
- ACtrlParams
- ACtrlTInputBundle
- ACtrlTOutputBundle
- ALoop
- ALoopApp
- ALoopDebugBundle
- ALoopIO
- ALoopInputBundle
- ALoopOutputBundle
- ALoopPar
- ALoopParIO
- ALoopParInputBundle
- ALoopParOutputBundle
- ALoopParParams
- ALoopParams
- AcqParallel
- AcqParallelIO

Scala Docs

gps

CA

```
class CA extends Module
```

A GPS L1 C/A PRN code generator module. IO:

satellite: Input(UInt), an int between 1 and 32 that selects which satellite's CA code to generate.

fco: Input(SInt), an NCO that drives the update frequency of the CA code

fco2x: Input(SInt), an NCO at 2x the frequency of fco that drives the update of the CA code

early: Output(SInt), The CA code, updated at zero-crossings of fco

late: Output(SInt), see CACodeShiftReg

punctual: Output(SInt), see CACodeShiftReg

done: Output(Bool), true for the cycle that a 1023-length CA code has fully finished

currIndex: Output(UInt), the current index of the 1023 length CA code being outputted

Linear Supertypes

Filter all members

Instance Constructors

```
new CA(params: CAParams)
```

create a CA code generator module

Value Members

Conclusion

Conclusion

- CHISEL was a great tool
  - Able to generate variants on submodules - reusability!
  - Scala was conducive to test automation
  - Ability to straightforwardly integrate software/hardware
  - Top-level integration workflow was very different from other HDLs - took some getting used to
- DspTools is critical for CHISEL DSP applications
  - FixedPoint!
- Connecting with RocketChip gives instant ability to test system as an SoC