GPS Operation

Last updated 3/7/24

GPS Operation

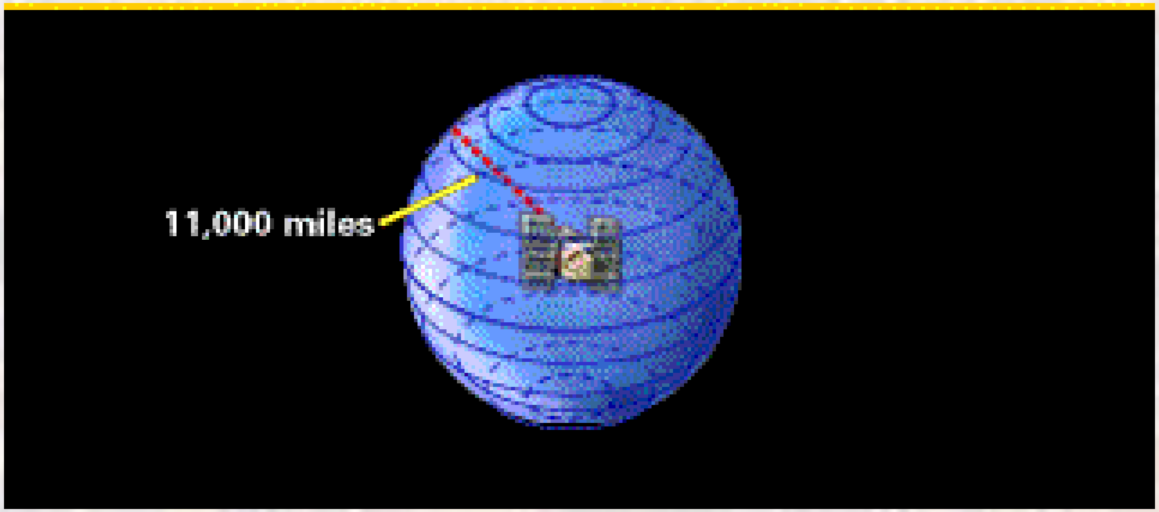
- The Basics
  - Measure distance using the travel time of radio signals

  - Need very accurate timing
  - Need to know exactly where the satellites are in space
  - Need to correct for any delays the signal experiences as it travels through the atmosphere

  - Use Trilateration to determine position
    - A method of determining the relative positions of objects using the geometry of triangles

GPS Operation

- Trilateration
  - Determine a position using 3 satellites
  - Assuming we can measure distance – with 1 satellite we know we are somewhere on the edge of the blue sphere – all points are 11,000 miles from the satellite

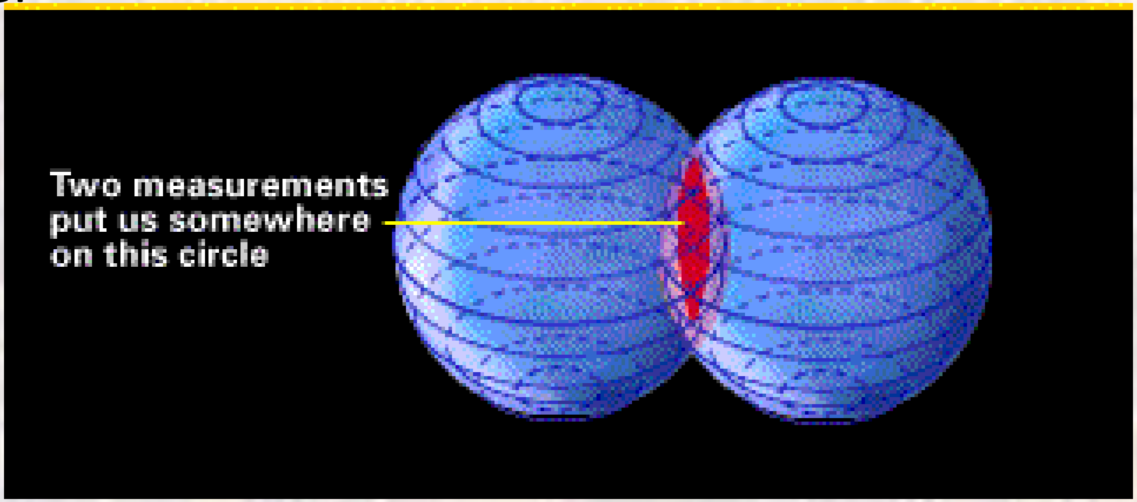


src: Trimble

Note: this is a general analysis – GPS is not at these distances

GPS Operation

- Trilateration
  - Determine a position using 3 satellites
  - With 2 satellites we know we are somewhere on the edge of the circle where the two spheres touch – points are 11,000 miles from one satellite and 12,000 miles from the other

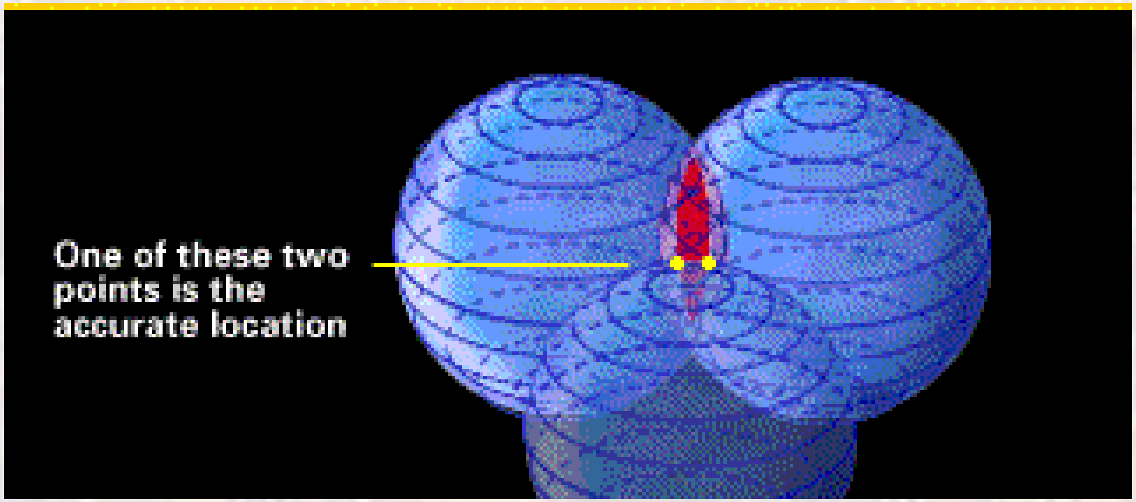


src: Trimble

Note: this is a general analysis – GPS is not at these distances

GPS Operation

- Trilateration
  - Determine a position using 3 satellites
  - With 3 satellites we know we are at one of two points where the three spheres touch – 11,000, 12,000, 13,000 miles from each satellite respectively

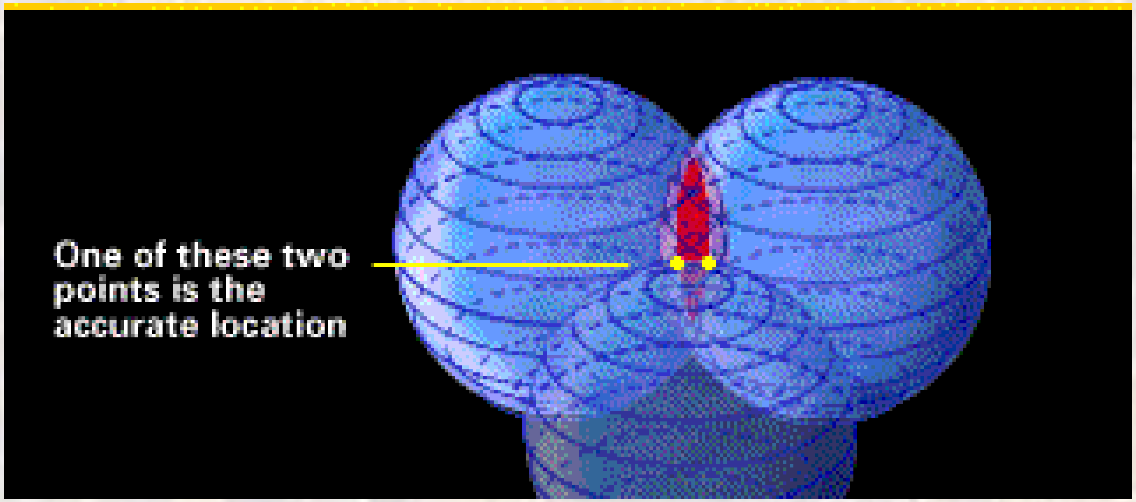


src: Trimble

Note: this is a general analysis – GPS is not at these distances

GPS Operation

- Trilateration
  - Determine a position using 3 satellites
  - Generally one of the points is not realistic, leading to the proper position.
  - An additional satellite can be used if both solutions are realistic – leading to a single point



src: Trimble

Note: this is a general analysis – GPS is not at these distances

GPS Operation

- Distance Measurement
  - Using precise clocks
  - Satellite transmits a code sequence using radio waves
    - Pseudo-random code
    - Travel at the speed of light - C
  - Receiver compares the code to a local copy
    - Time shift in the code → distance measurement
    - $d = C \Delta t$

  - When the satellite is directly overhead
    - d = 20,200Km
    - $\Delta t \approx 67.3$ms

GPS Operation

- Accurate Clocks
  - Satellites
    - Onboard Atomic Clocks
    - Tuned to the oscillations of a rubidium atom
    - Accurate to approximately 14ns
  - Receivers
    - Obviously can't have atomic clocks (> $10K)
    - Use a 4th satellite signal
      - Assuming accurate satellite clocks, but an error in the receiver clock
      - All 4 signals will not match to a single location
      - Find the receiver clock time shift that makes all 4 match
        - receiver clock error correction → accurate position
    - As a side benefit, the receiver now has atomic clock accuracy

GPS Operation

- Satellite Location
  - Placed high enough into space to conform to well known orbital mechanics - ~20,200Km
  - Spaced such that 4 satellites are in view from anywhere on earth (typically 5 are visible)
  - Pre-programmed with expected location information based on position and orbit
  - Position and velocity monitored by very accurate radar by the Department of Defense
    - Errors are called ephemeris errors
    - Caused by gravitational pull of the sun and moon, and by solar flares
  - Position updates transmitted to the satellite
    - New position included in the Pseudo-random transmission to be used by the receiver

GPS Operation

- Errors and error correction
  - Radio wave velocity varies as it traverses the path from satellite to ground
    - Ionosphere – outer layer
      - Charged particles
      - Can be modeled – but still results in errors
    - Troposphere – inner layer subject to weather
      - Changes with water vapor, temperature, pressure
      - Hard to model – but creates limited error

  - Multi-path errors
    - Signal bounces off multiple objects near the ground
    - Causes multiple received signals – slightly delayed from the direct path
    - Signal processing can largely manage these errors
    - Urban Canyons – lots of multipath and limited satellite view

GPS Operation

- Errors and error correction

Standard GPS	Typical Error in Meters (per satellites)
Satellite Clocks	1.5
Orbit Errors	2.5
Ionosphere	5.0
Troposphere	0.5
Receiver Noise	0.3
Multipath	0.6

GPS Operation

- Differential GPS
  - Add fixed location receivers
    - Known – very accurate position
  - Place the fixed receivers close to areas where high accuracy is desired ~100mi
    - Harbors, railyards, truck depots, airports
  - GPS signals to the mobile receiver and fixed receiver traverse nearly the same paths and conditions
  - Use the Fixed receiver to measure all the errors except for multipath (localized)
  - Transmit the error correction factors to the mobile receiver via a radio channel

GPS Operation

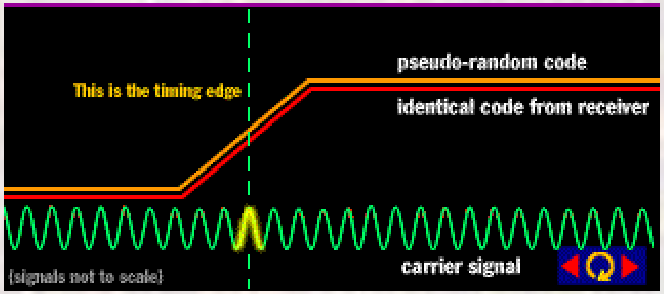
- Differential GPS

Differential GPS	Typical Error in Meters (per satellites)
Satellite Clocks	0
Orbit Errors	0
Ionosphere	0.4
Troposphere	0.2
Receiver Noise	0.3
Multipath	0.6

GPS Operation

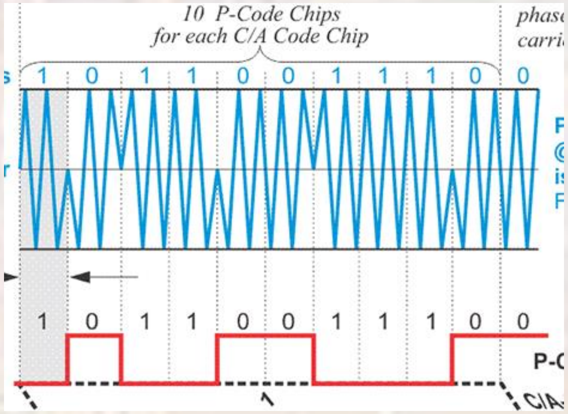
- Signal Detection

  - Code phase – compares pseudo random codes
    - Bit rates ~1MHz
    - 300m “wavelength”
    - With 99% match → Errors of a few meters



src: Trimble

  - Carrier phase
    - Match the carrier signals
    - 1.56GHz → 19cm wavelength
    - Use code phase matching to get close
    - Enhanced circuitry to match the carrier signals
    - With 99% carrier match → 3-5 mm accuracy



src: PSU geog862

GPS Operation

- Dual Frequency Transmission

  - Low-frequency signals get "refracted" or slowed more than high-frequency signals in a given medium
  - Compare the delays between two carriers (L1 and L2) to get an atmospheric correction value
  - Limited application because L2 is only available to the US military

  - Newer systems have included a second carrier – L5, to allow dual carrier operation

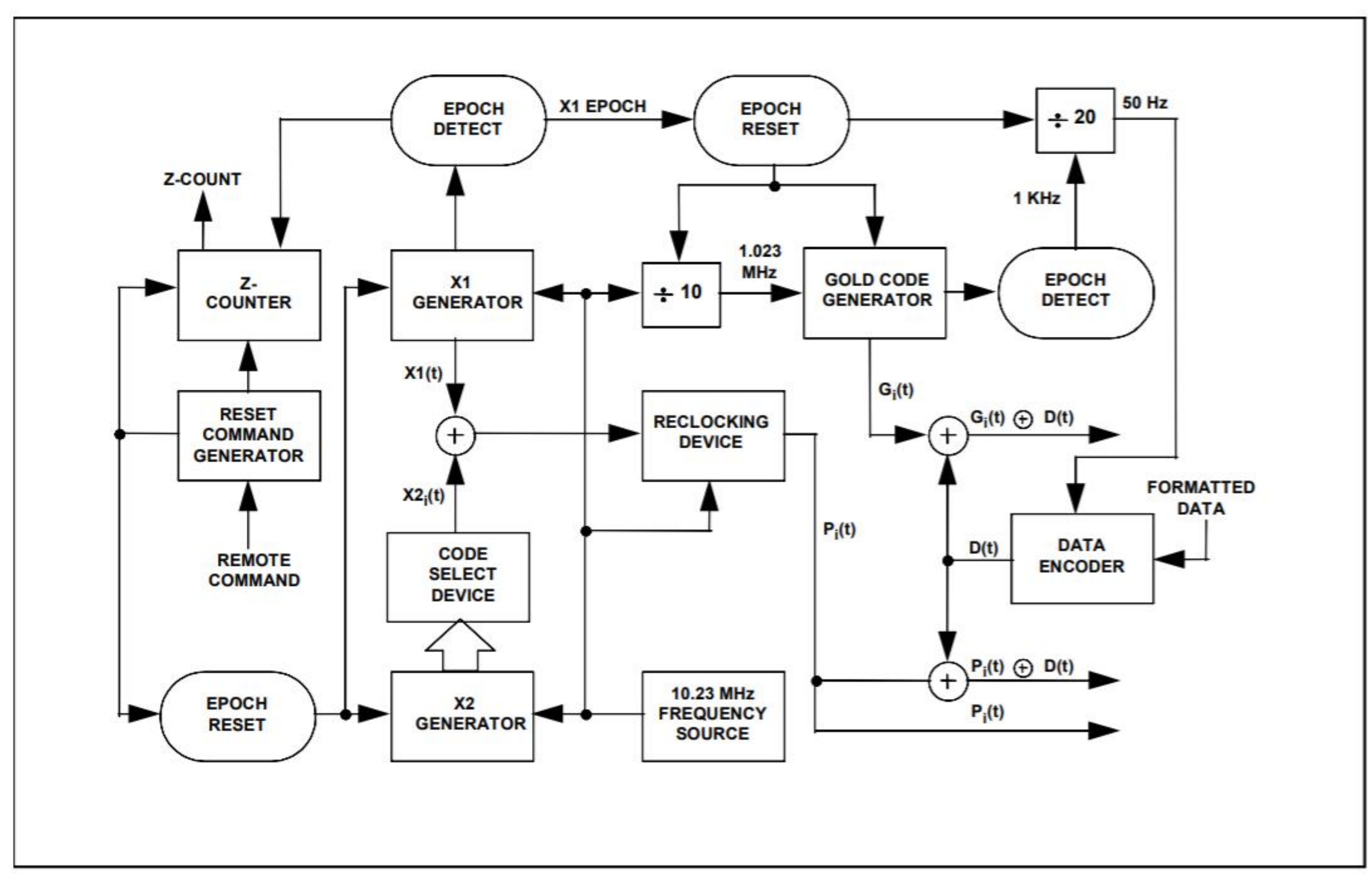
GPS Operation

- Pseudo-Random Code
  - The PRN P-code for SV ID number i, for i = 1 to 37, is a ranging code, Pi(t), of 7 days in length at a chipping rate of 10.23 Mbps. The 7 day sequence is the modulo-2 sum of two sub-sequences referred to as X1 and X2i; their lengths are 15,345,000 chips and 15,345,037 chips, respectively. The X2i sequence is an X2 sequence selectively delayed by 1 to 37 chips thereby allowing the basic code generation technique to produce a set of 37 mutually exclusive P-code sequences of 7 days in length.

src: gps.gov, IS-GPS-200K.pdf

GPS Operation

- Signal generation



src: gps.gov, IS-GPS-200K.pdf

GPS Operation

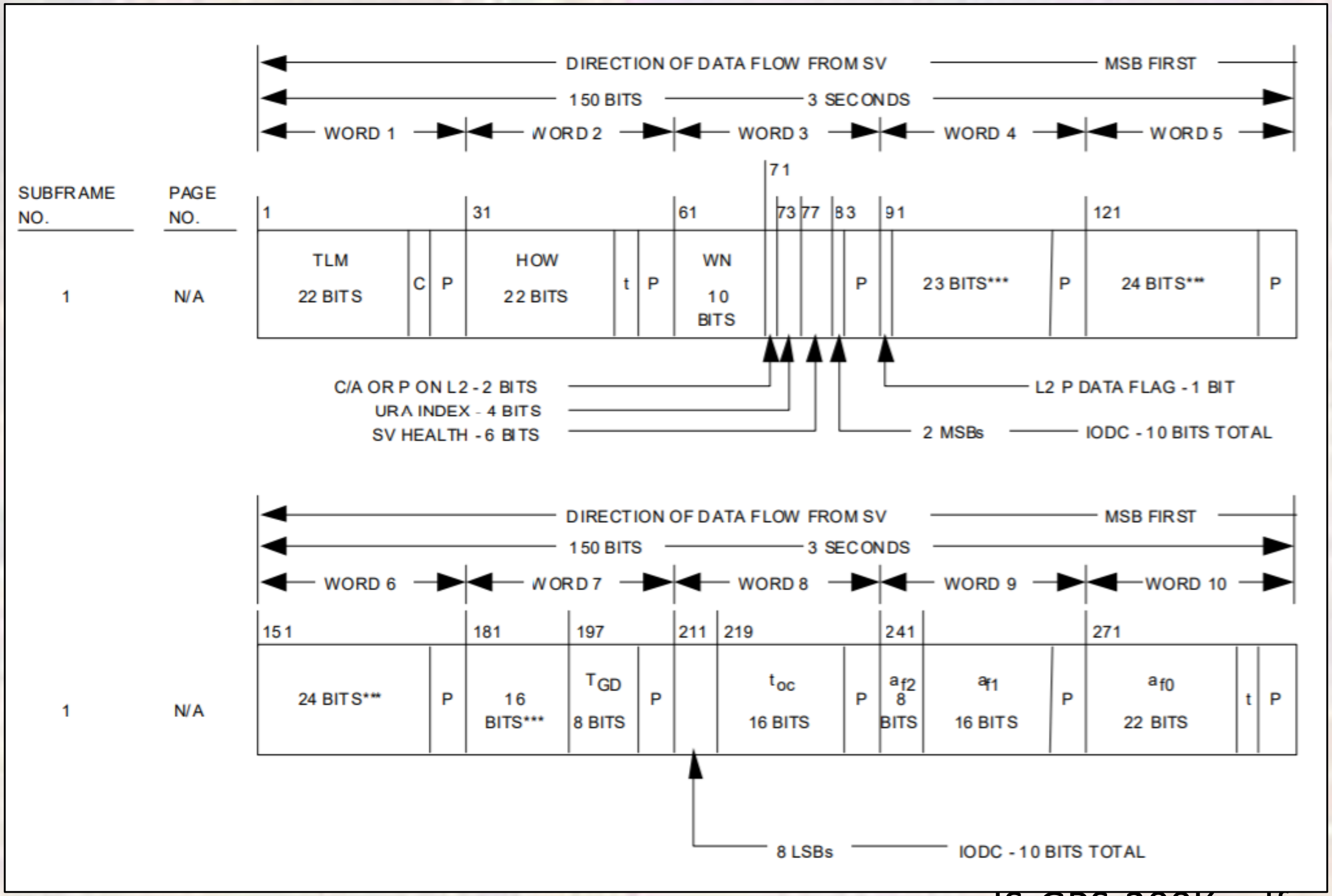
- Message Structure

  - The message structure shall utilize a basic format of a 1500 bit long frame made up of five subframes, each subframe being 300 bits long. Subframes 4 and 5 shall be subcommutated 25 times each, so that a complete data message shall require the transmission of 25 full frames. The 25 versions of subframes 4 and 5 shall be referred to herein as pages 1 through 25 of each subframe. Each subframe shall consist of ten words, each 30 bits long; the MSB of all words shall be transmitted first

src: gps.gov, IS-GPS-200K.pdf

GPS Operation

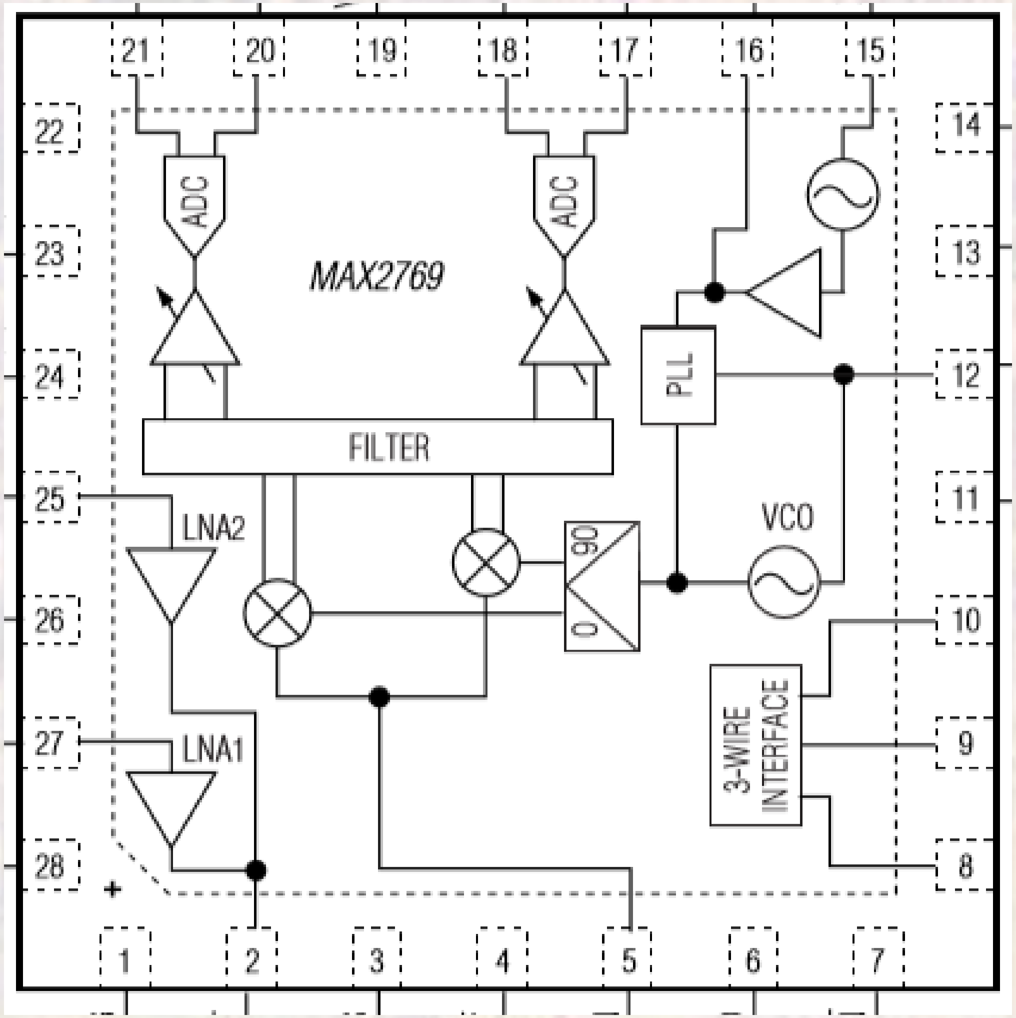
- Message Structure
  - 1 of 11 structures



src: gps.gov, IS-GPS-200K.pdf

GPS Operation

- Chipsets – Maxim – basic receiver



GPS Operation

- Chipsets – Broadcom – Full feature receiver
  - Supports two frequencies (L1+L5)
  - Integrated multi-frequency GNSS baseband and RF front end for simultaneous reception of GPS, GLONASS, BeiDou (BDS), Galileo (GAL), and SBAS satellite systems
  - Support for position batching, geofencing, sensor fusion and sensor navigation
  - ARM-based 32-bit Cortex-M4F (CM4)
  - ARM-based Cortex-M0 (CM0)