Importance of GPS
More Applications Coming
Drawbacks of GPS

• **Dependent:** We have become reliant on this now critical infrastructure for nearly all aspects of our lives.

• **Easy to Jam:** Can take out a city block with a 20 Watt GPS jammer.

• **Expensive:** It takes a Billion $ / year just to operate a devoted constellation.
Changing Space

• There has been a resurgent interest in building large constellations of low Earth orbiting (LEO) satellites to deliver broadband internet to the world.

• Proposals have been announced by OneWeb with support from Virgin and Qualcomm, SpaceX with support from Google, and Samsung.

• Can these be leveraged as a platform for navigation by piggybacking with a hosted navigation payload.
GPS (32) + Iridium (66)
Iridium (66)
OneWeb (648)
SpaceX / Samsung (4000+)  

What if each hosted navigation payload, with signals comparable to GPS?
All Operational Satellites

1,305 Operational Satellites Today
Position Error
\[ \sigma_{\text{VERT}} = \text{VDOP} \sigma_{\text{URE}} \]

\[ \sigma_{\text{HOR}} = \text{HDOP} \sigma_{\text{URE}} \]
Error Budget

• What is our 3D position error?

\[ \sigma_{URE} \times PDOP \]

User Range Error

Position Dilution of Precision
GDOP as a Function of Constellation Size

Geometric Dilution of Precision (GDOP)

Number of Satellites

GLONASS
Galileo
BeiDou
GPS

MEO
GSO

Teledesic
OneWeb
SpaceX

500 km
700 km
1100 km
1400 km
Error Budget

• What is our 3D position error?

\[ \sigma_{\text{URE}} \times \text{PDOP} \]

- User Range Error
- Position Dilution of Precision
Clocks

• Each GPS satellite has 4 atomic clocks onboard.
• Each costs millions of dollars and consume \( \sim 40 \text{ Watts} \).
• They are too costly in terms of $’s and power for low cost LEO.
Chip Scale Atomic Clock (CSAC)

- **Low Power:** <120mW

- **Small Size:** 17 cc volume, 1.6”x1.4”x0.5”

- **Low Cost:** ~1000$, projected to be ~$300 in coming years.

- **Trade off:** ~100x worse at one day compared to GPS clocks.

- Can get comparable performance if you update once per orbit instead of once per day.
Total Ionizing Radiation Dose
For a 5 Year Mission with 5 mm Aluminum Shielding
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For a 5 Year Mission with 5 mm Aluminum Shielding

Conclusions

• Navigation from LEO:
  – Strength in numbers: more satellites and better geometry allows looser constraints on the URE (Orbit + Clock).
  – Less harsh radiation environment allows for COTS components.
  – Closer satellites means stronger signals and resistance to jamming.
  – Constellation is more robust to single satellite failures.