The Development of the GPS System ...1964 to 1978

Chief Engineer, Design/Development of the initial GPS Satellite, Rockwell International

Hugo Fruehauf

Scientific & Technical Consultant

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September. 2014

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Rev. B, 25 Oct. 2014

World War II

Germany: ~1.6 – 2.0M tons of Allied bombs
Euro Theater: ~2.8M – 3.1M tons
~4.4M – 5.1M tons Total

For Germany alone
~600,000 – 1M Civilian Casualties
~95% Infrastructure destroyed

- Allied Strategy

- Cities of >80,000 population, ~100 cities/targets
- Bombing from ~10km altitude
- More than 10% of bombs didn't explode

- Anti-Aircraft Guns

*Ref: Wikipedia and a host of other websites

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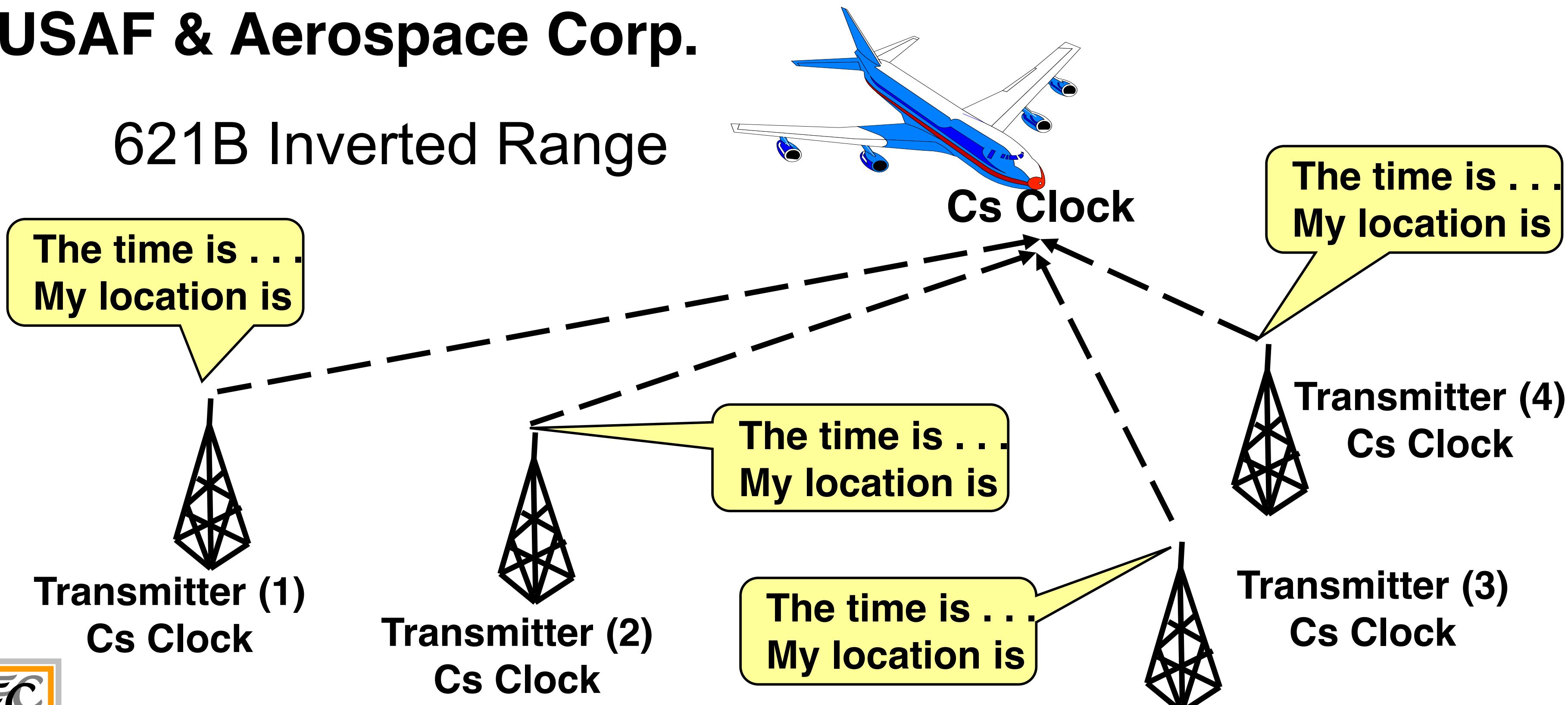
Future Warfare Strategy

- Regime change, Tactical Scenarios
- Absolute minimum Collateral Damage
- Precision Targeting would be required
- **Ultimate System would require:**
  - Global Coverage
  - 24/7 Availability
  - Precision 3D Positioning, Navigation, and Time
  - 2σ Precision Targeting Dependability
  - Military Secure Signal (Mil-Com'l Coexistence)
  - CONUS Satellite Control & Orbital Maintenance

Earlier 2D Nav Systems & 621B Project

- Early ‘60s to ‘70s, **2D** Global Navigation became reality:
  - **Transit** Sats, ***Navy,*** Global, ~300m
  - **Loran-C** Grd Sta’s, ***CG/Navy,*** Coastal, ~200m
  - **Omega** Grd Sta’s, ***CG mainly***, Global, <1km
- **Breakthrough mid-60s, for 3D navigation - 621B Project, USAF & Aerospace Corp.**

621B Inverted Range



Further Developments; 621B & NRL

- NRL research, mid to late-60s with passive ranging:
  - Launch of **Timation I & II** satellites, 1967 & 1969, with other gov agencies contributing to concept validations

- Navy & USAF rivalries for control of 3D navigation programs solved by forming a Joint Program Office, headquartered at LAAFB, California (next to LAX)
  - “JPO” ***(USAF-Navy)***; other services sent representatives
  - PMs: Col. Brad Parkinson (USAF) & Cmdr. Huston (USN)
  - Right hand to Brad, Cap. Gaylord Green (USAF)
- With the military and gov agencies now teamed to succeed, a GPS system began to emerge
- Gov engaged industry in 1973 to help develop a final GPS concept from available research/data and new ideas

Brad Parkinson, Ph.D
Stanford U, Emeritus

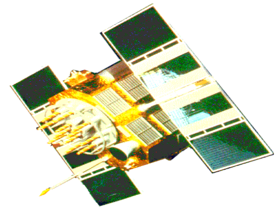
No doubt, the most significant person that made GPS happen (then, Col. Parkinson, USAF)

- Pentagon & Capital Hill political savvy to get program funded
- Systems Design Engineering Expert
- Brilliant Program Management

GPS emerged in (3) Segments

GPS program divided into (3) Segments:

(1) Satellite Segment



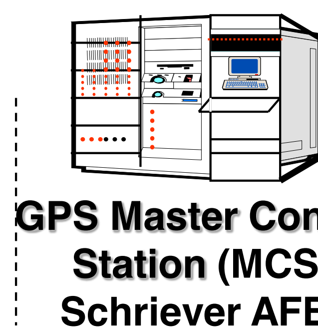
(then) Rockwell International, Seal Beach CA

(2) User Segment

(then) mainly Magnavox, Torrance CA
and Rockwell-Collins, Cedar Rapids, IA

(3) Control Segment

Master Control Station
+ Monitor Stations
(MCS + MS's)



GPS Master Control Station (MCS-Schriever AFB)

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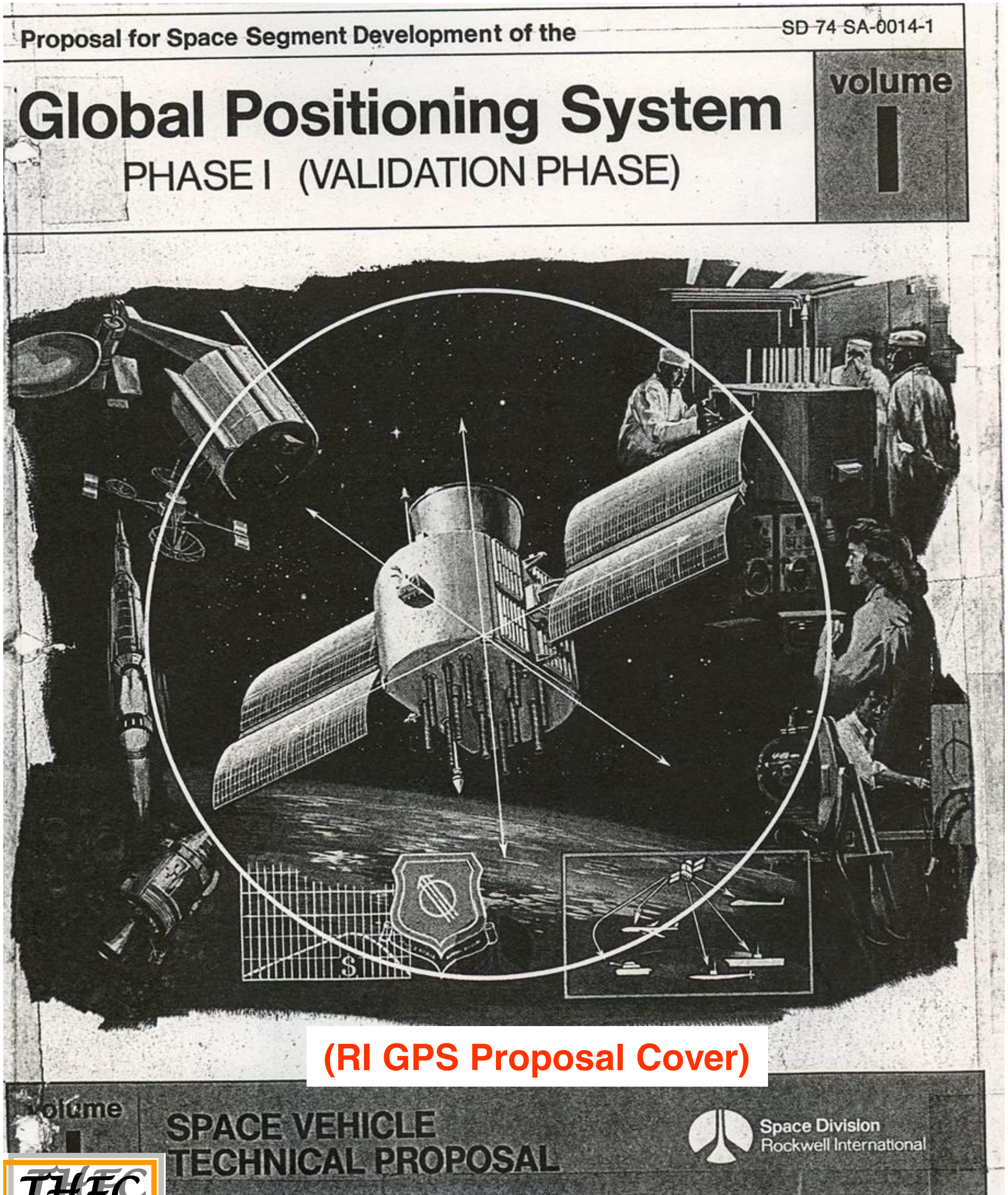

(RI GPS Proposal Cover)

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DNSDP (GPS) Proposal 1974; Rockwell's winning design

Other bidders:

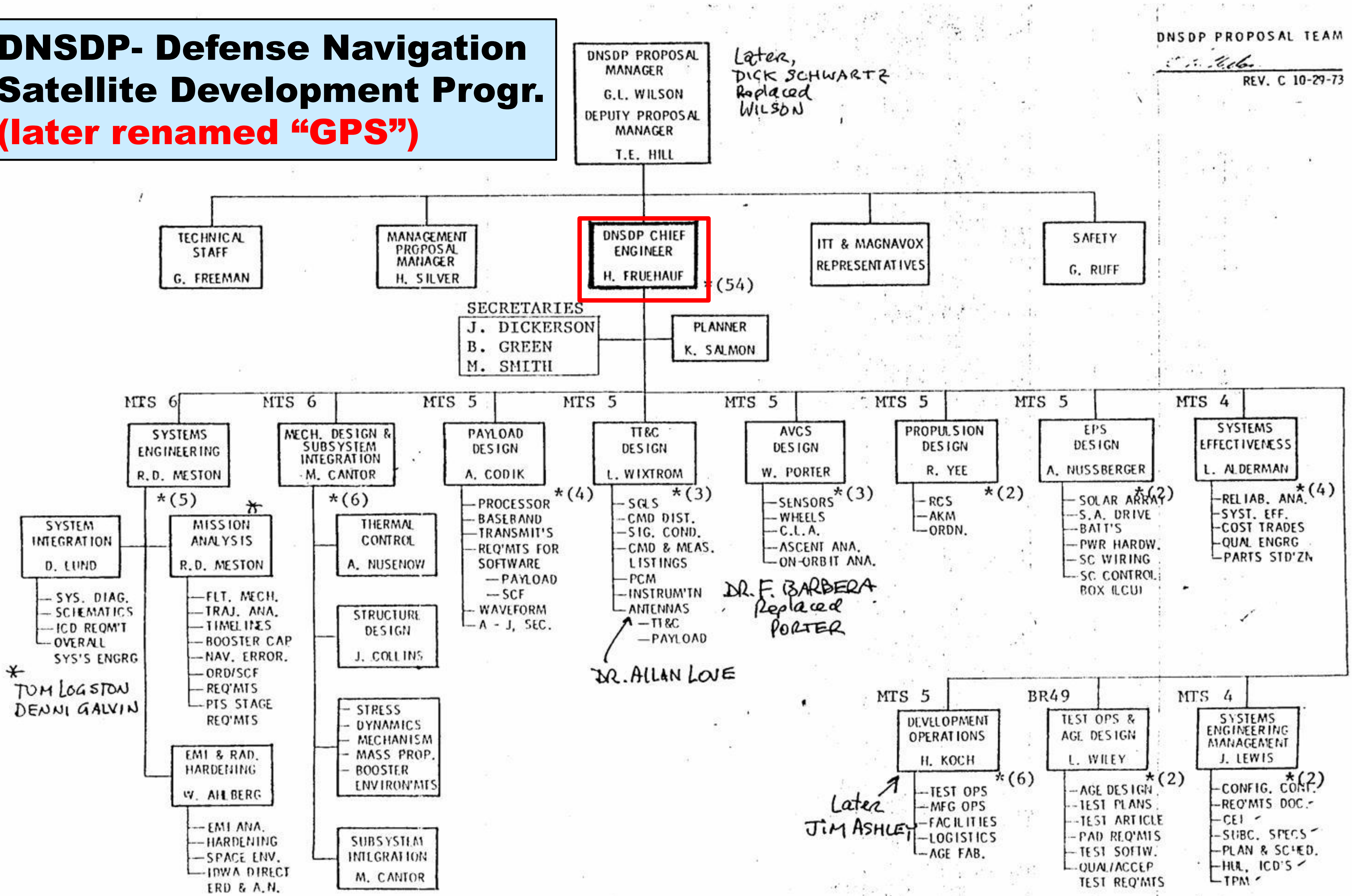
- RCA,
- Philco Ford
- Grumman

Giants in the Satellite Industry – not bid:

- GE
- Hughes

- **Proposal System**
- Initial Gov/Mil R&D
- RFI-Industry Invt'mt & Gov?
- RFP-Mainly Industr .Invt'mt, sometimes Gov help

DNSDP- Defense Navigation Satellite Development Progr.
(later renamed "GPS")



Rockwell Design Team (1973-75)

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GPS Technical Challenges

- Global Coverage and 24/7 Availability
- Precision 3D Navigation and Positioning
- 2σ (~95%) - Targeting Dependability
- Precision Timing and Synchronization
- CONUS satellite updates
- Including UTC; (604,800 s/week & 1023-0 bit Weeks + leap secs)

Week 0 started at 00:00:00 UTC on Sun. Jan.6th 1980, and '<u>rolled over</u>' after exhausting 1023 bits of weeks (~19.7yrs); 23:59:47 UTC, Sat. Aug. 21st 1999

- Spread Spectrum Quadra-Phase C/A+P(Y) + 50 bit Data Signal Format
- C/A as acquisition-aid for long P(Y)-code Mil Signal
- Shaped Beam Antenna
- (4) Sats for 3D Nav (User RCVR w/o atomic clocks)
- Relativity Compensation
- Selective Availability (SA) – PNT accuracy of C/A
- 1,400 lbs limit for initial GPS Sats; 21 launches on Atlas-F's
- Military control of GPS Sats and Ground Control Segment (MCS)
-

GPS Biggest Risk – the Atomic Clock

- Efratom's Ernst Jechart & co-founder Gerhard Hùbner - inventors of the small (~10x10x10 cm) Rb Vapor Atomic Clock
- Werner Weidemann – Engineering
- All worked for Rohde & Schwarz – Munich Germany

Ernst Jechart
Efratom, GmbH

Gerhard Hübner
Efratom, GmbH

Werner Weidemann
Efratom, GmbH

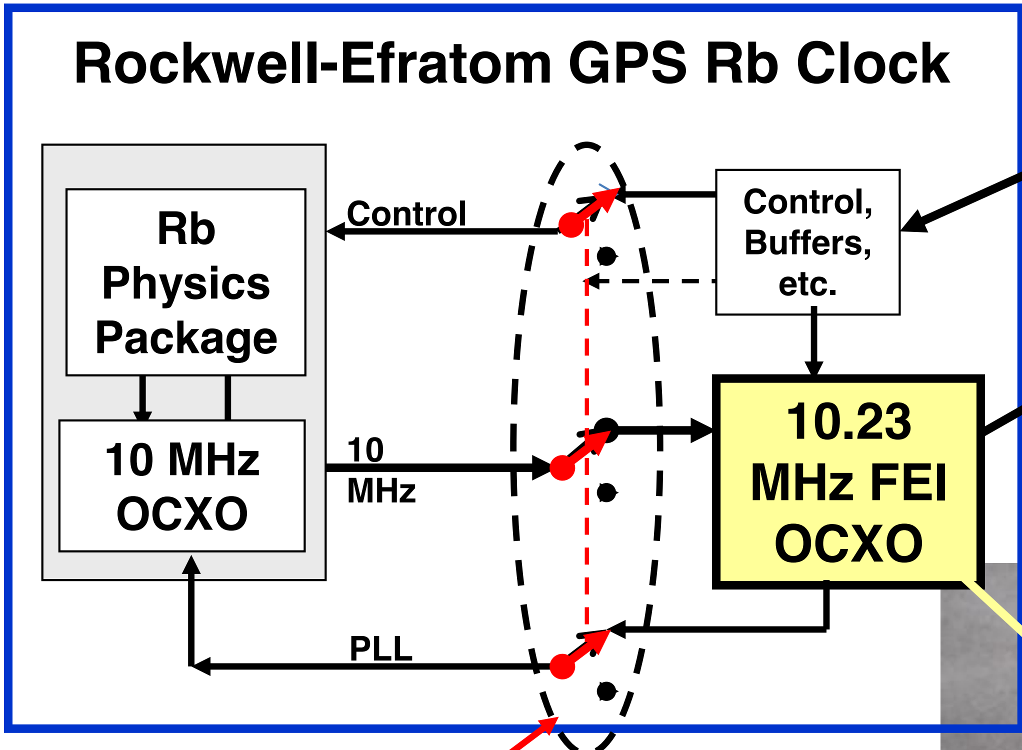
Issues:

- 1st chaotic meetg
- Language
- Foreign Co.
- Very Small
- Overwhelmed
- Citizenship
- Space Knowhow (RI-Efr Team)
- Rb Confidence
- Efratom 1978

- Ernst 1991 (54)
- Werner 2008 (65)

Efratom GmbH, Munich + later Irvine, CA

GPS Rb Clock + ‘Std-alone’ OCXO

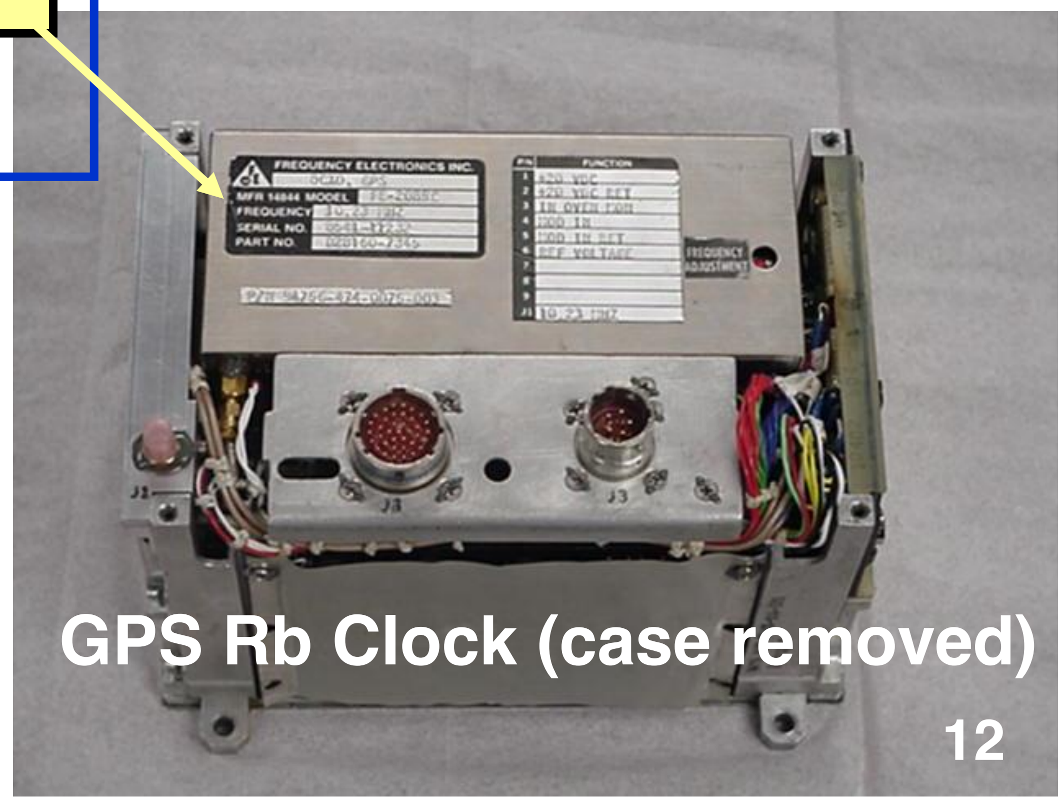


Satellite Clock Control

10.23 MHz Output

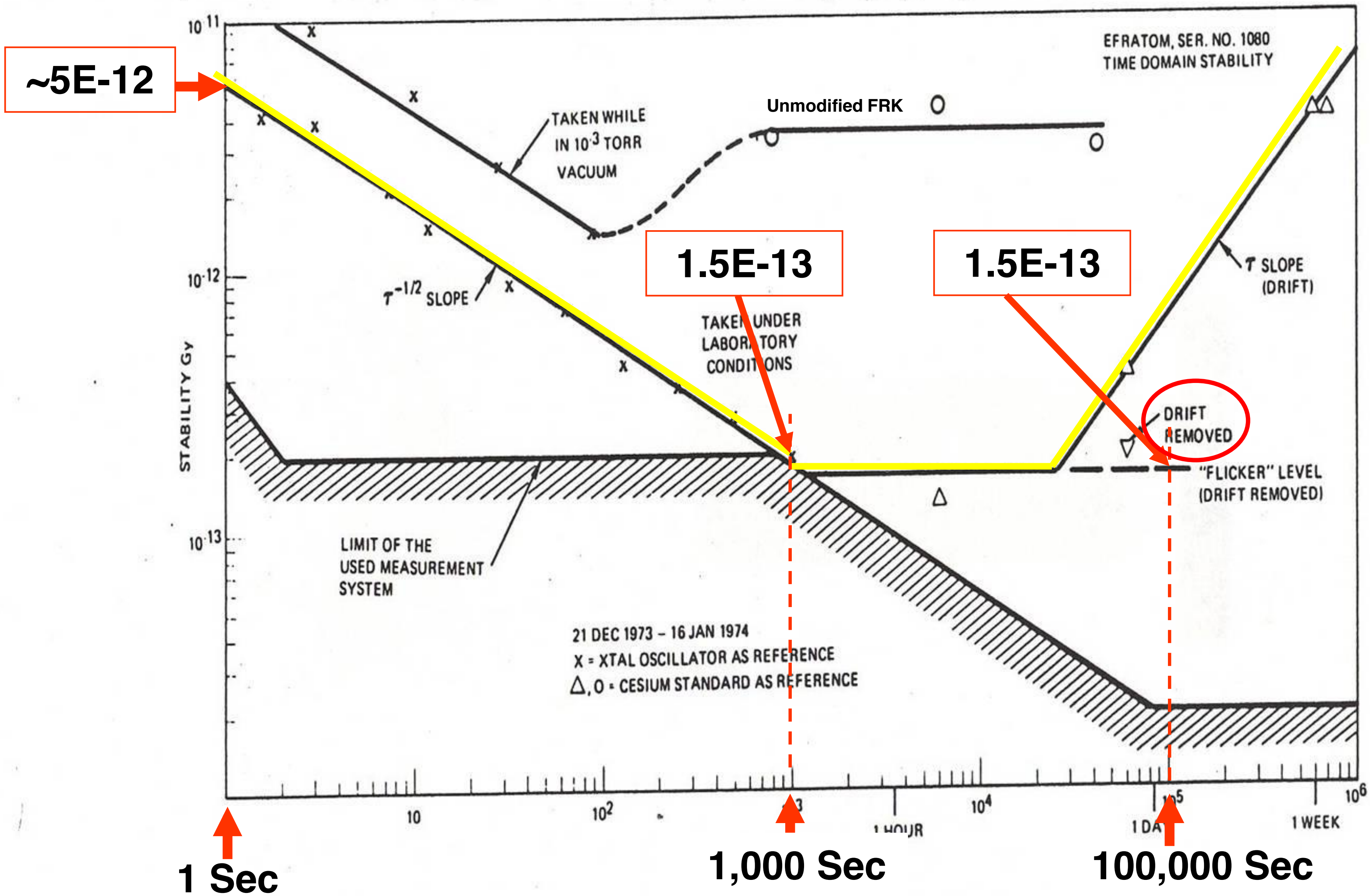
10.23 MHz for ‘Coherence’
x 145 = 1,575.42 MHz, (L1)
x 120 = 1,227.60 MHz, (L2)

The ‘saving grace’ *Political Switch* to isolate the Atomic side



GPS Rb Clock (case removed)

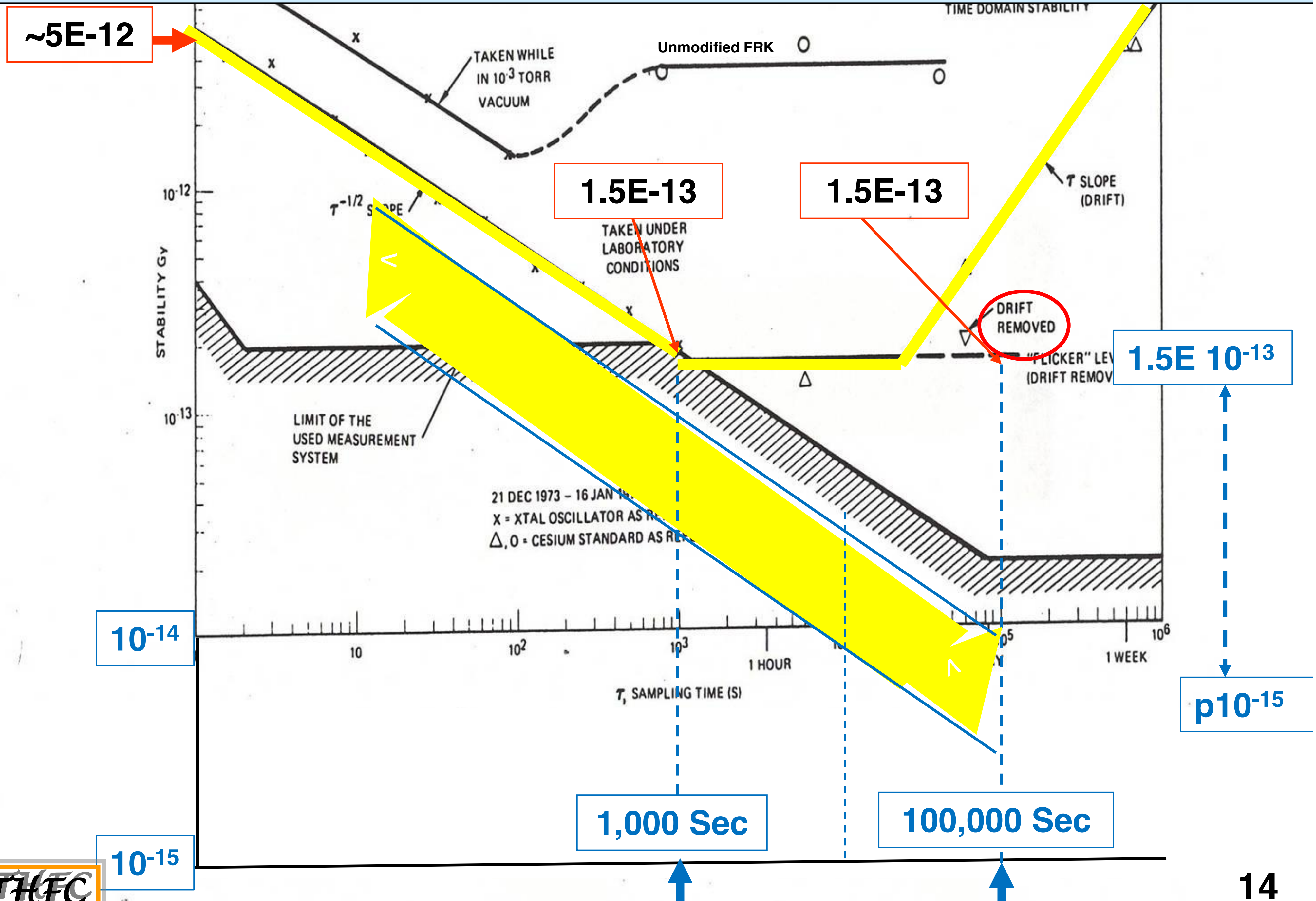
RI-Efratom Rb Clock Stability 1974



DNSDP (GPS) Proto-type Rad Hard Rb - Performance, RI-Efratom FRK-Rb, 1974,

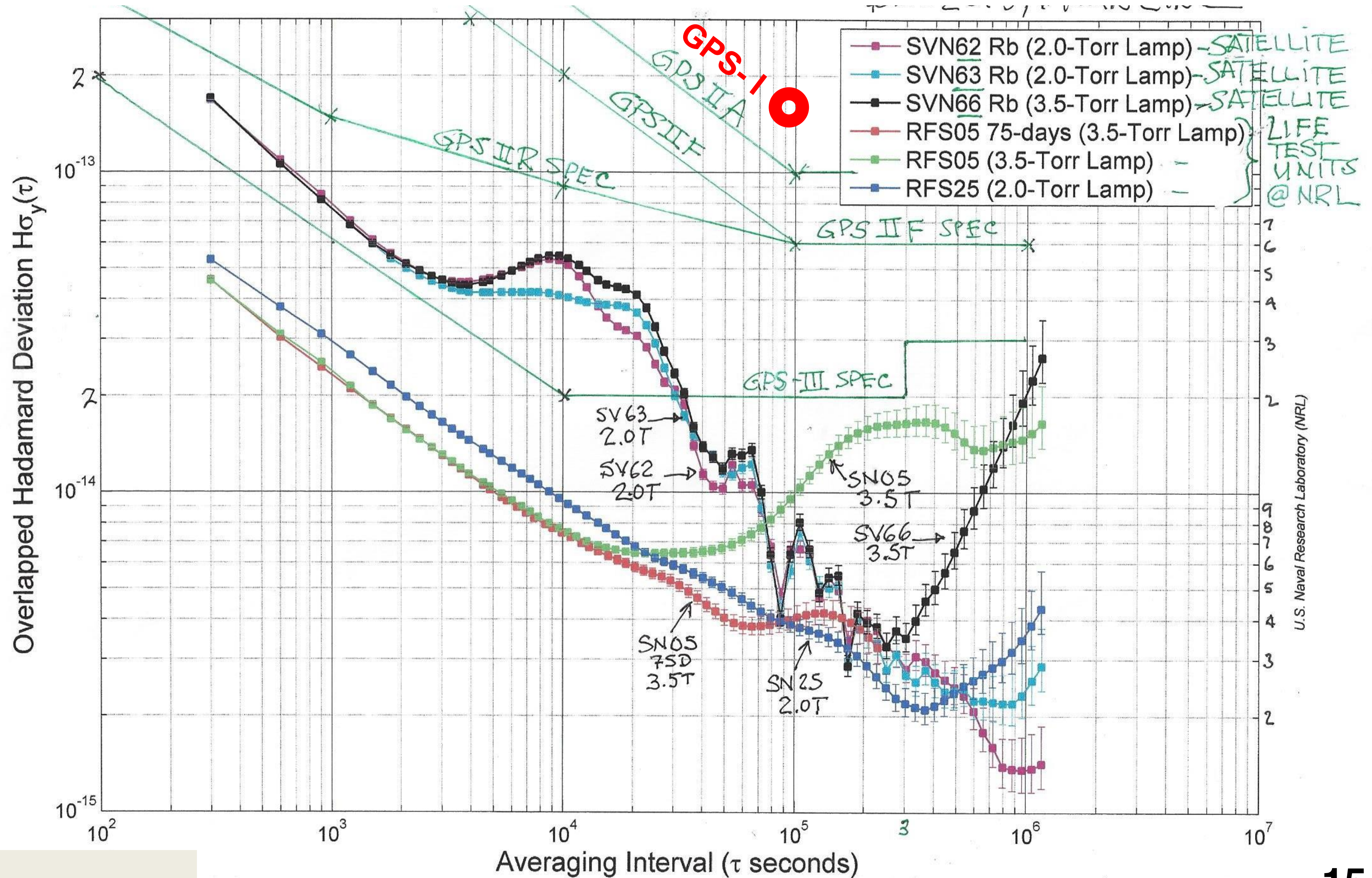
Hugo Fruehauf, Werner Weidemann, Dale Ringer, Chuck Wheatley, Norm Rudie

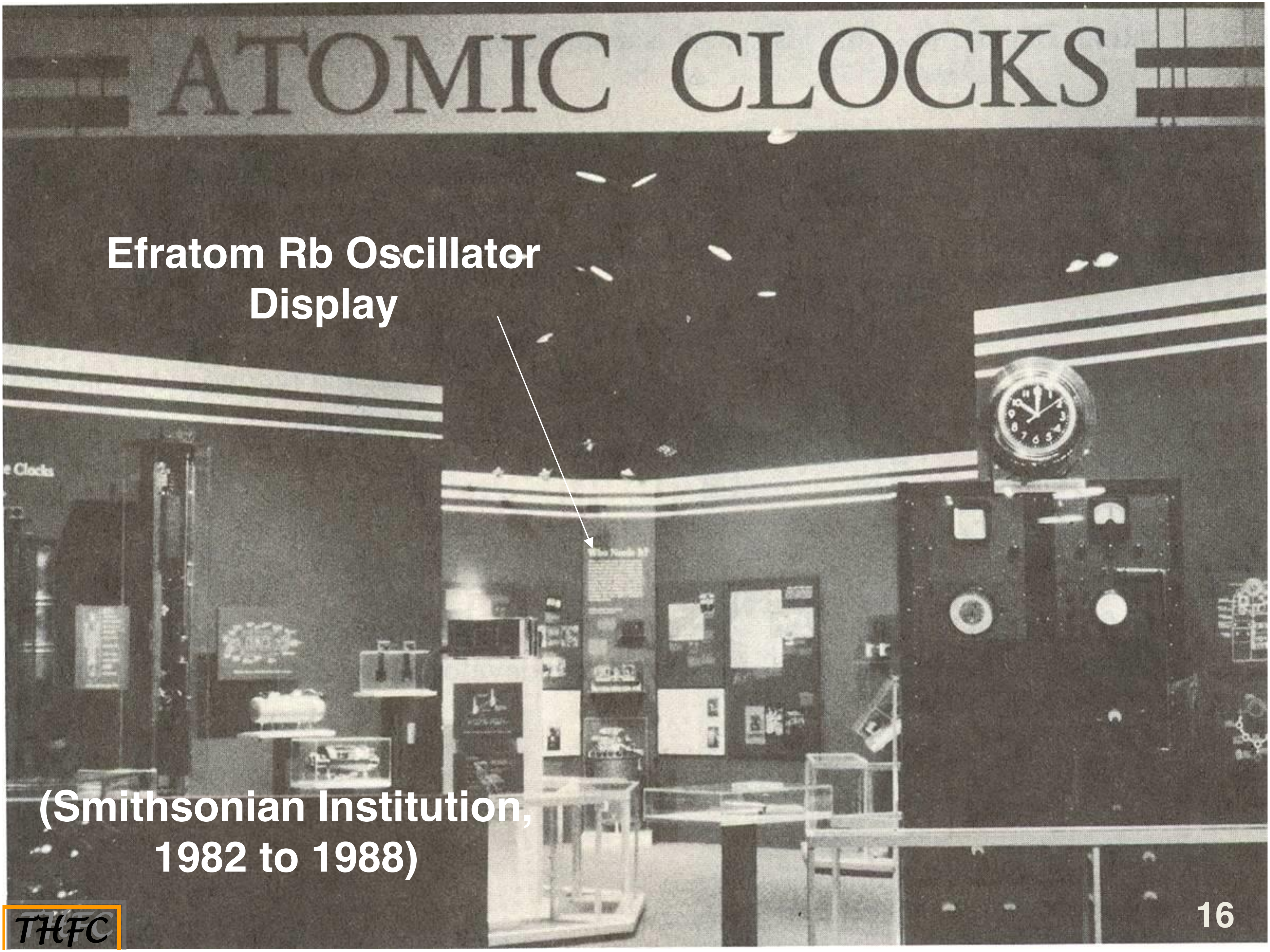
Today's GPS Rb Clock Stability



GPS Blk IIF RFS Stability Performance

Chart from: "GPS Block IIF Atomic Frequency Standard Analysis"; F. Vannicola, R. Beard, etc. (NRL)



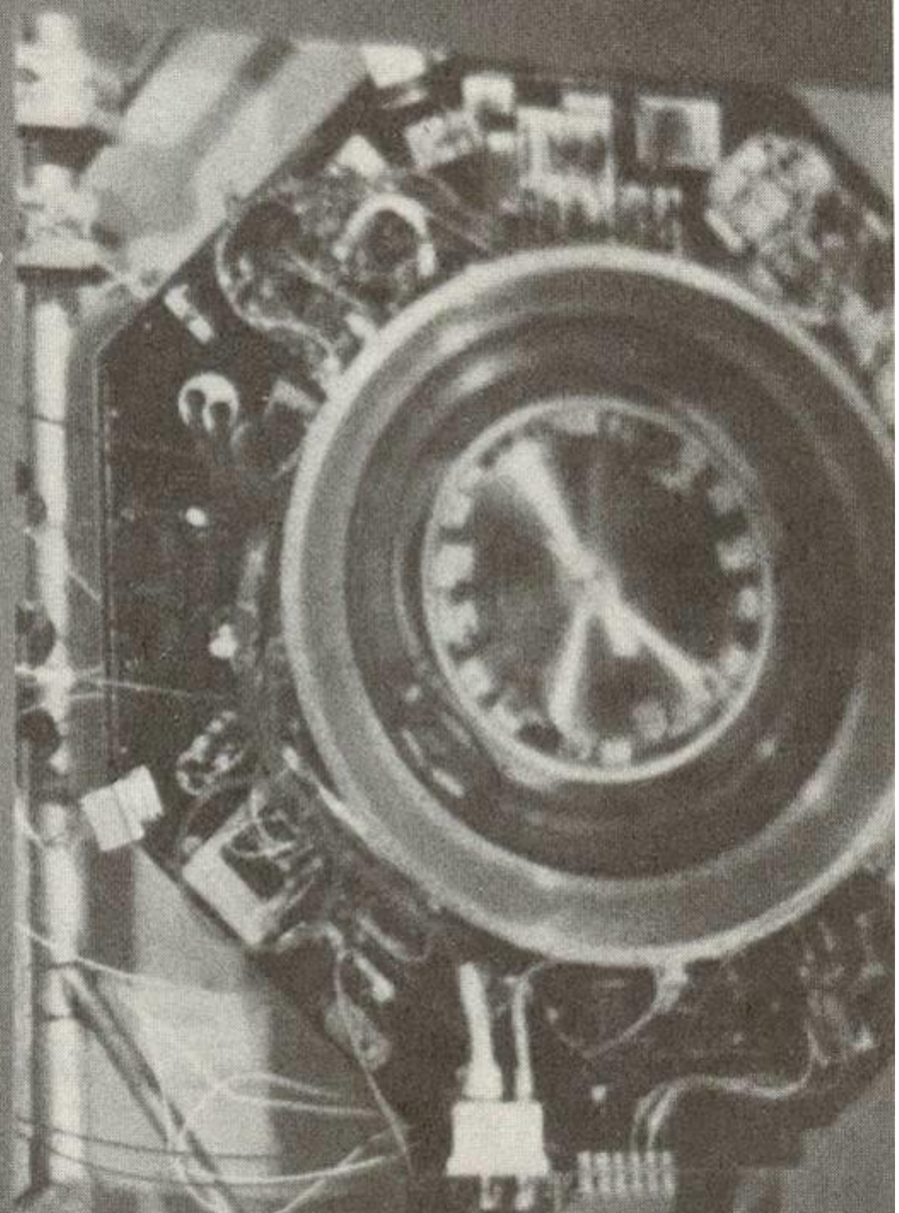

ATOMIC CLOCKS
Efratom Rb Oscillator Display
(Smithsonian Institution, 1982 to 1988)
THFC

NTS-1 nearly complete, May 1974

Different names have been used for the satellites of the GPS at different stages of its development. The first to carry atomic clocks were the Navigation Technology Satellites (NTS), numbers 1 and 2, built by the Naval Research Laboratory and launched in July 1974 and in June 1977. Subsequent satellites called Navstar-1, -2, etc., have been built by Rockwell International under contract to the U.S. Air Force.

Atomic clocks on board NTS-1

Two *EFRATOM* Model FRK rubidium-vapor frequency standards, similar to the flight back-up exhibited here, sit on the ring-shaped instrument deck of the NTS-1 satellite. On July 14, 1974 they were launched into orbit.



(Smithsonian Institution, 1982 to 1988)

Satellite Navigation Clock History to GPS

(Hugo Fruehauf, Ron Beard, Brad Parkinson; 01-13-2010)

Program / (Service)	Dates	# of Sats / Nav Method	Nav Dim	Clocks	Ops Status
NNSS (Transit); (Navy-JHU/APL)	1964 to ~1990	(7) Sats; Doppler meas.	2D	(1) Quartz Oscillator	Was fully operational
Timation I & II; (Navy- NRL)	1967 and 1969	(2) Sats; Ranging Tones	2D	(1) Quartz Oscillator	Experimental
Navigation Technology Satellite-1 (NTS-1) (Navy- NRL)	Launch July 1974	(1) Sat; Hazeltine 621B Transm., No Data; Ranging Tones	2D	(2) Efratom Com'l Rb's, modified by NRL to perform in space, +(1) Quartz	Experimental: (1) Rb operated for more than one year; (1) Rb failed early
NTS-2; (Navy-NRL); USAF/JPO provided Nav. Payload	Launch July 1977	(1) Sat; ITT Eng'g PRN Nav. Pkg. from USAF-JPO; + Rang'g Tones	2D	(2) Proto space qualified FTS Cs + (2) Quartz Osc's	Although intended to be part of the initial (4) Satellite Nav testing, NTS-2 failed before nav testing began
GPS Operational Prototypes, award'd to Rockwell in 1974 by USAF-JPO, now "GPS Wing"; named GPS in Dec 1973; DNSDP* during early proposal effort	Devel'mt 1973-75; Rockwell Block-I launches began Feb.1978	(4) Sats, Production ITT PRN Nav. Pkg	3D	(3) RI-Efratom Rb's on the 1st (3) GPS Sats; 4th Sat & up, (3) RI-Efratom Rb's + (1) 2nd gen. FTS Cs**. 1st Cs on GPS 4 failed after 12 hrs; Cs ok - GPS-5 & up	GPS Constellation of (4) Rockwell Block-I GPS Satellites for the initial Navigation Test Program +(1) NRL NTS-2 Sat, but failed before nav testing began (see above)

* Defense Navigation Satellite Development Program

** Later, Block-II and -IIA, flew (2) Rb and (2) Cs

GPS Technical Challenges

- Global Coverage and 24/7 Availability
- Precision 3D Navigation and Positioning
- 2σ (~95%) - Targeting Dependability
- Precision Timing and Synchronization
- CONUS satellite updates
- Including UTC; (604,800 s/week & 1023-0 bit Weeks+ 13 leap sec)
- Spread Spectrum Quadra-Phase C/A+P(Y)+ 50 bit Data Signal Format
- C/A as acquisition-aid for long P(Y)-code Mil Signal
- Shaped Beam Antenna
- (4) Sats for 3D Nav (User RCVR w/o atomic clocks)

  - Cold War Issue ~(-)25dB below
  - Existing 2D Nav
  - Commercial Mrkt
  - Spoofing Problem

- Relativity Compensation
- Selective Availability (SA) – PNT accuracy of C/A
- 1,400 lbs limit for initial GPS Sats; 21 launches on Atlas-F's
- Military control of GPS Sats and Ground Control Segment (MCS)
-

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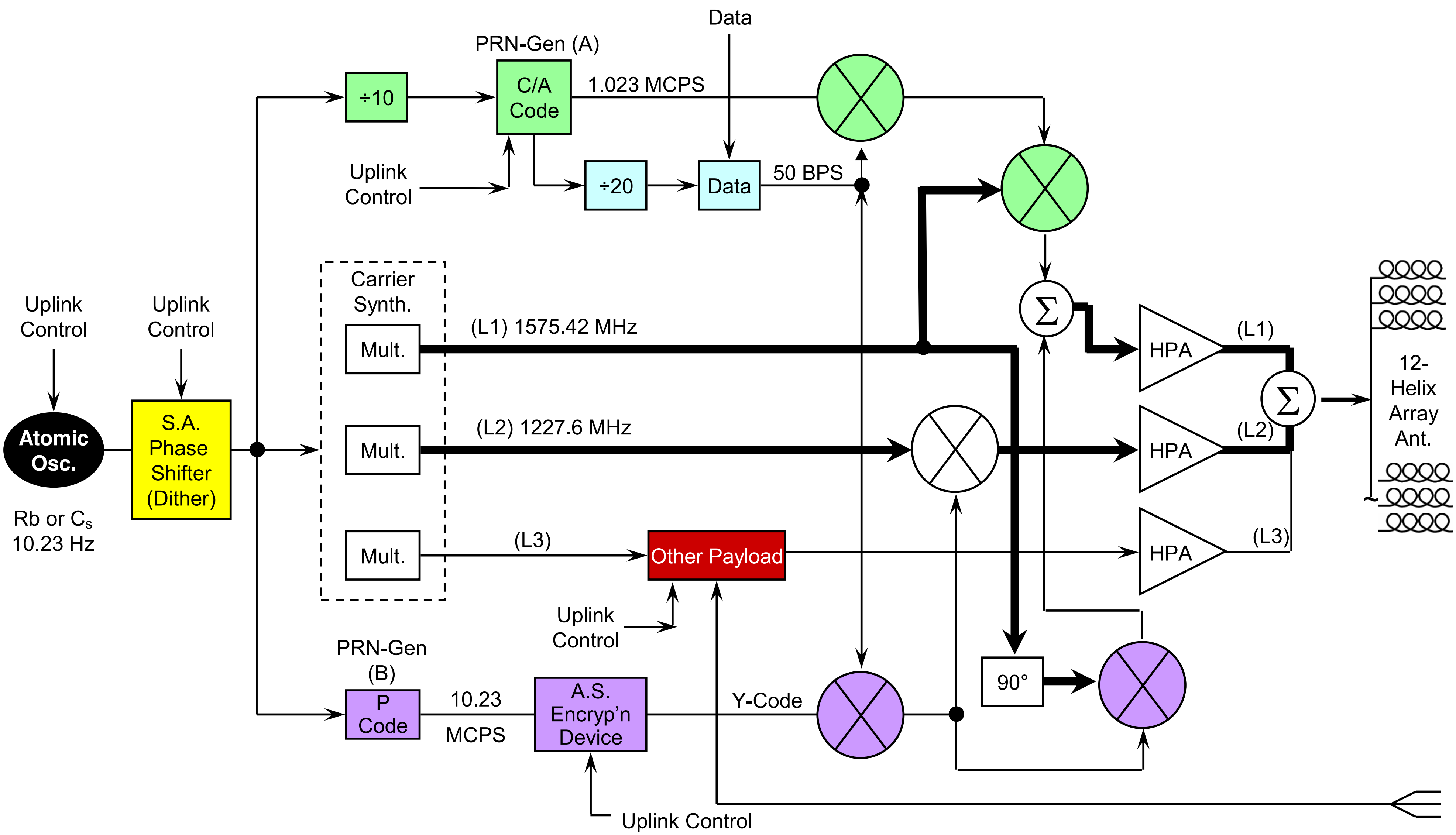
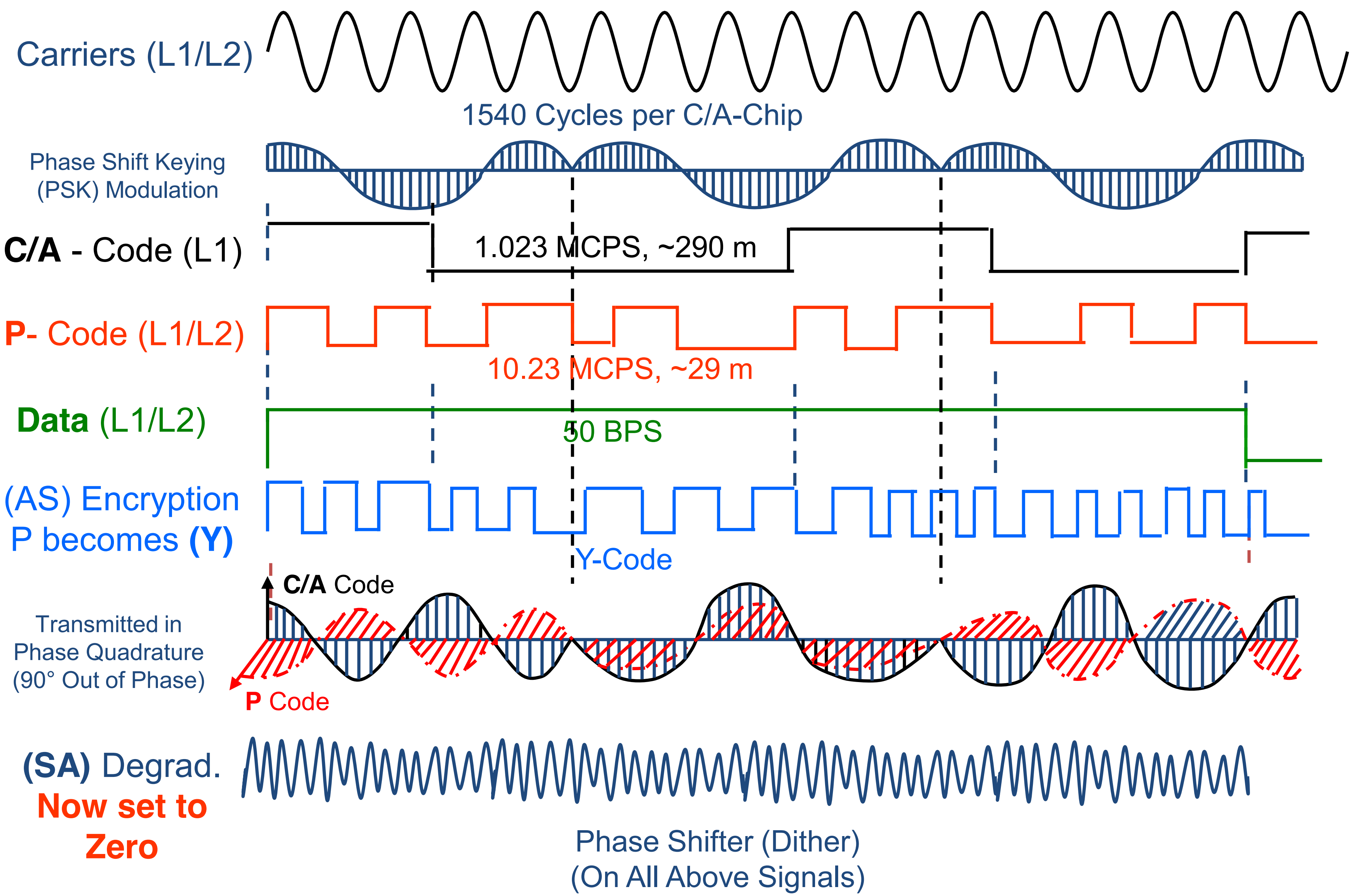
GPS Navigation Payload (original)



QPSK C/A, P(Y) & Data Signals (original)



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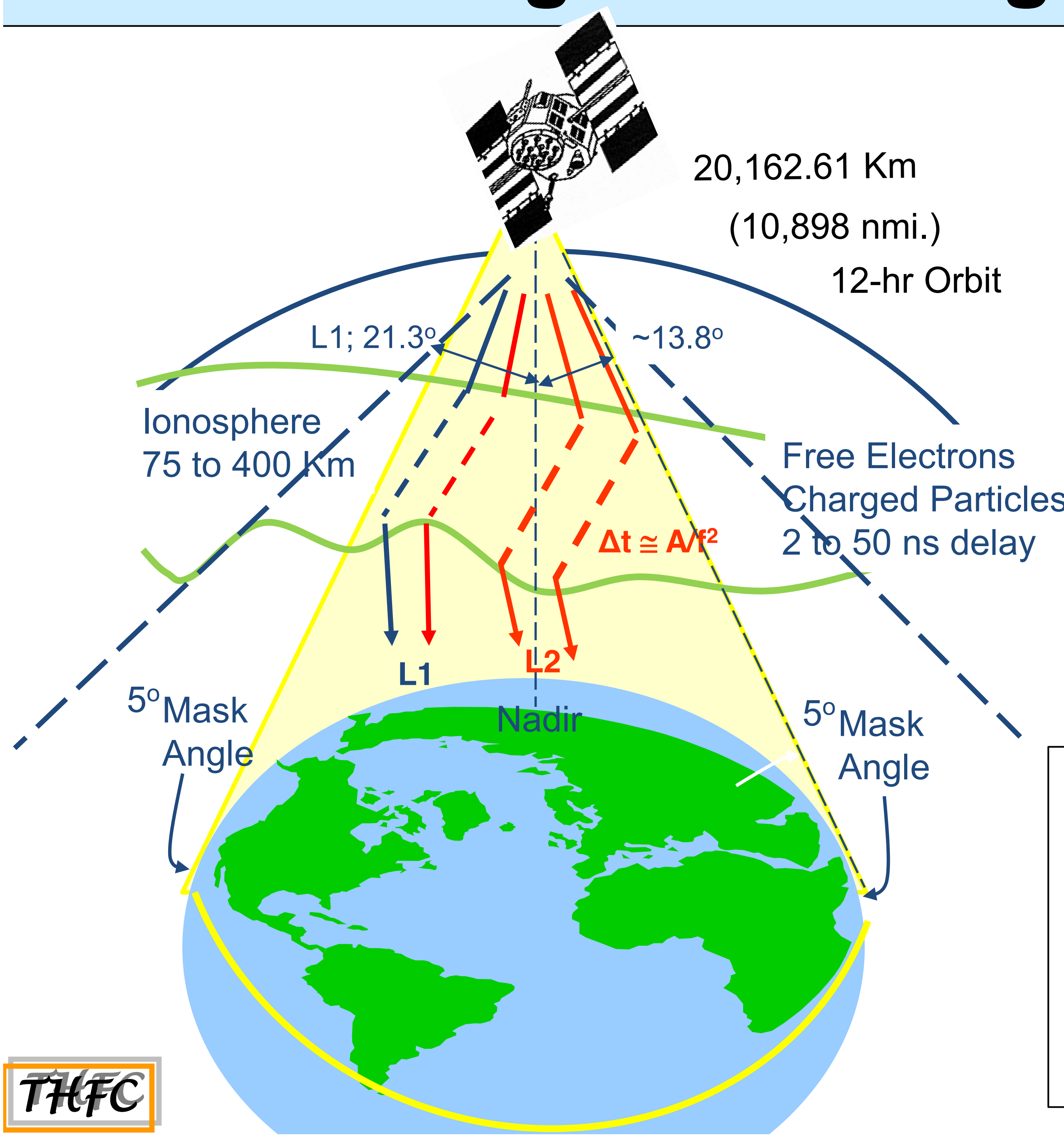
Original GPS Signals



- **L1 1575.42 MHz**
  Open Signal
  C/A-Code 1.023 Mcps,
  + 50 bps Data
- **Encrypted Signal**
  P(Y)-Code 10.23 Mcps
  + 50 bps Data
- **L2 1227.6 MHz**
  Encrypted Signal
  P(Y)-Code 10.23 Mcps
  + 50 bps Data
- **L3 – Other Payload**

- **New signals being added to GPS SVs**
- **L1C**
- **L1-M**
- **L2C**(M&L)
- **L2-M**
- **L5 -** 1176.450 MHz
- **L4 -** 1379.913 MHz **??**

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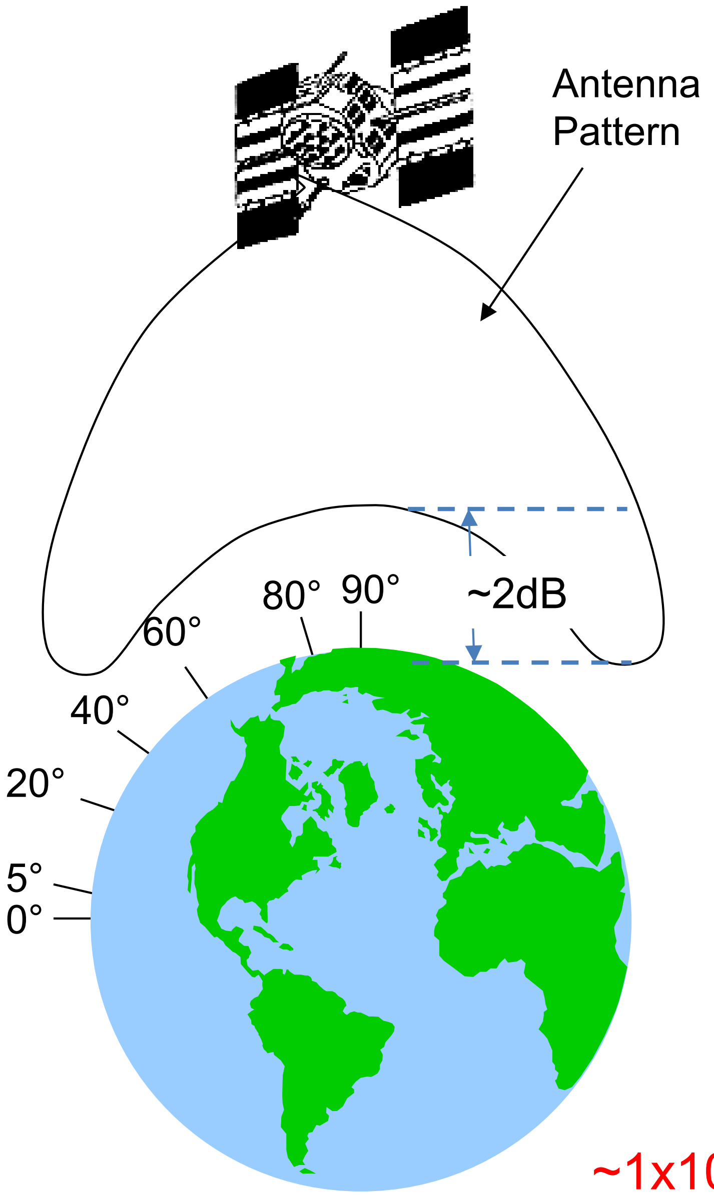
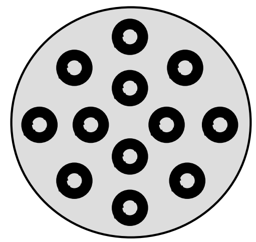
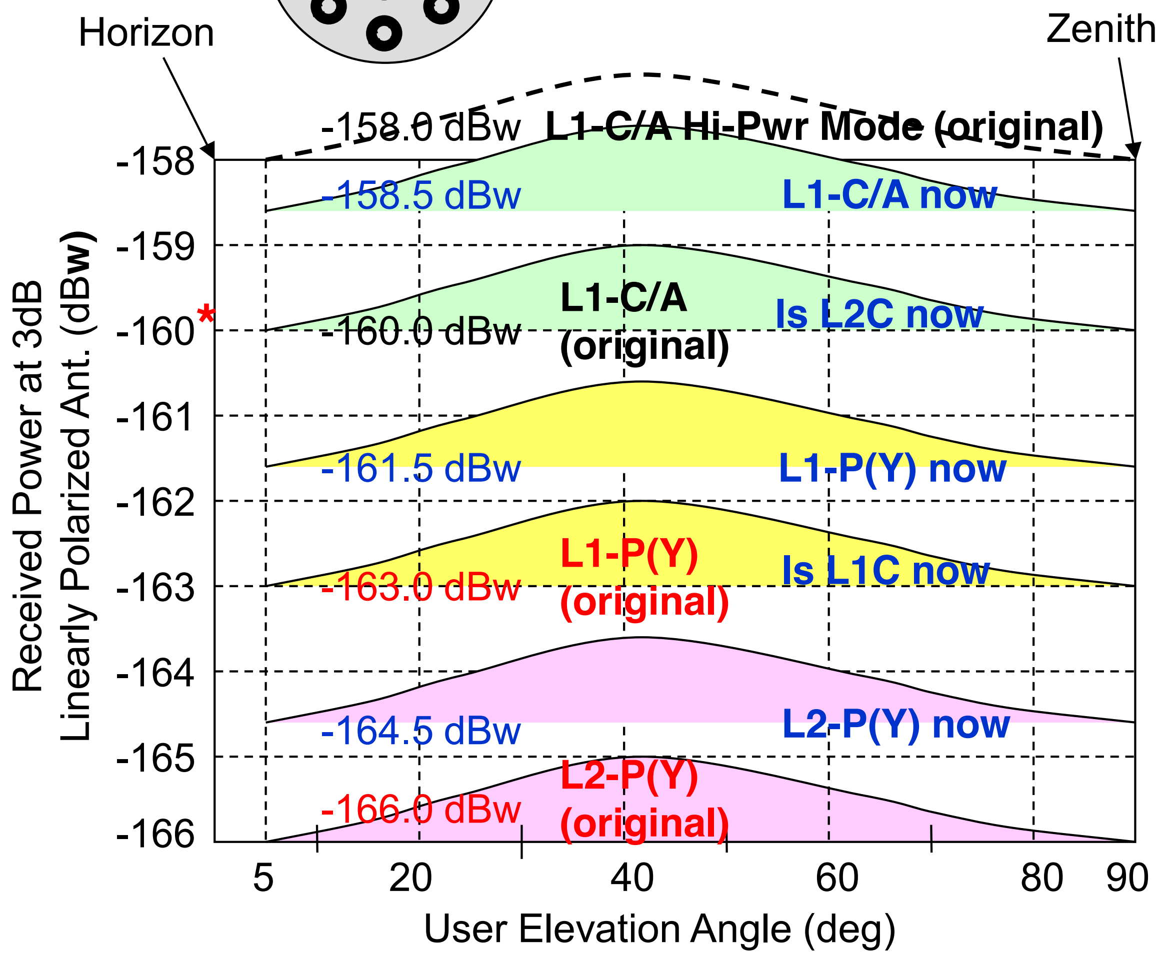
Shaped-Beam (12) Helix Phased Array Antenna, RHC Polarized)





GPS Antenna: 12 Element
L-Band Helical Phased Array
RHCP transmitted signal



~1x10^{-16} watts*

Received Power vs. SV Elevation Angle

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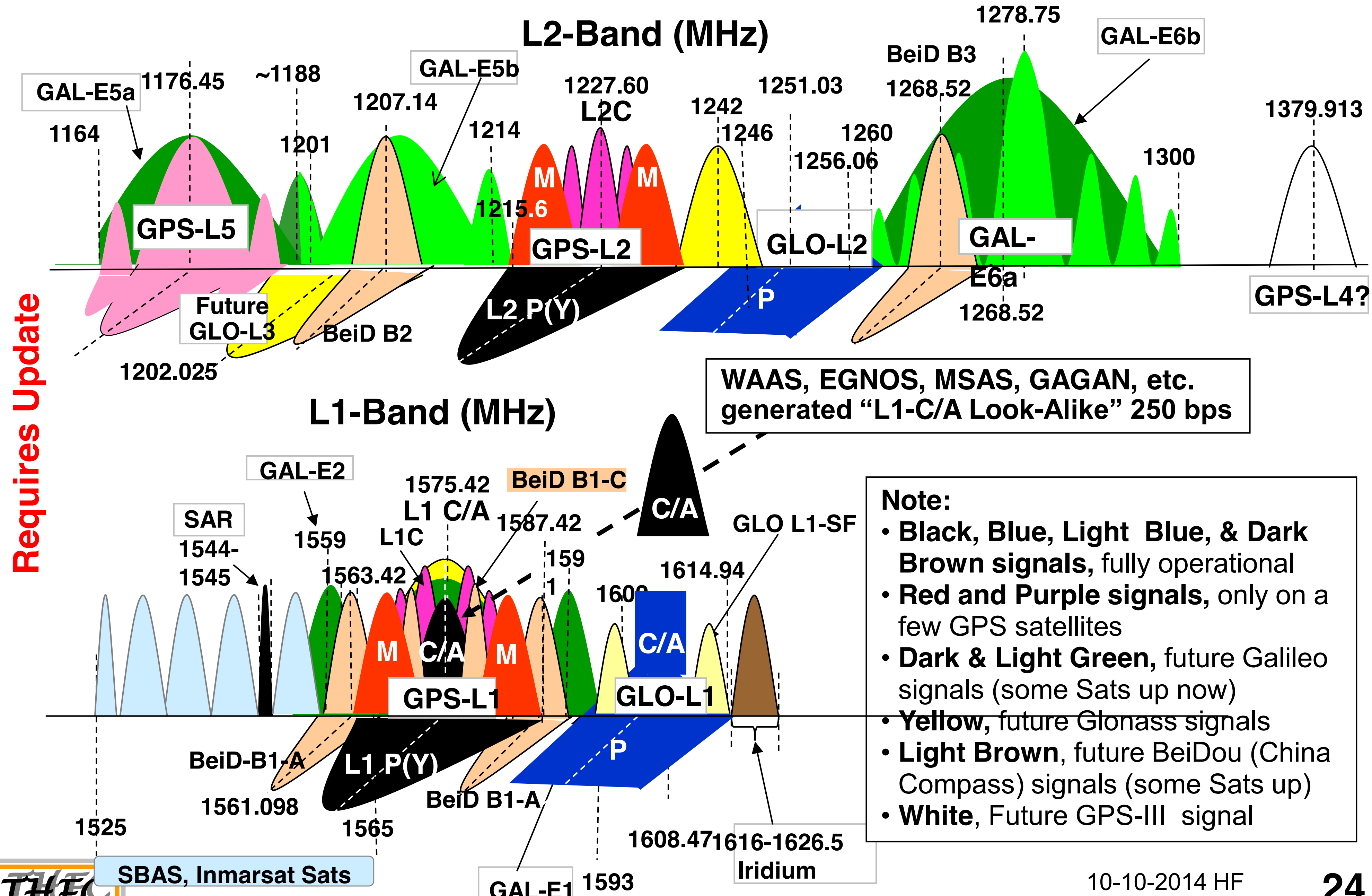
L-Band Navigation-related Frequencies

GPS, Glonass, Galileo, BeiDou, SBAS, Iridium, SAR

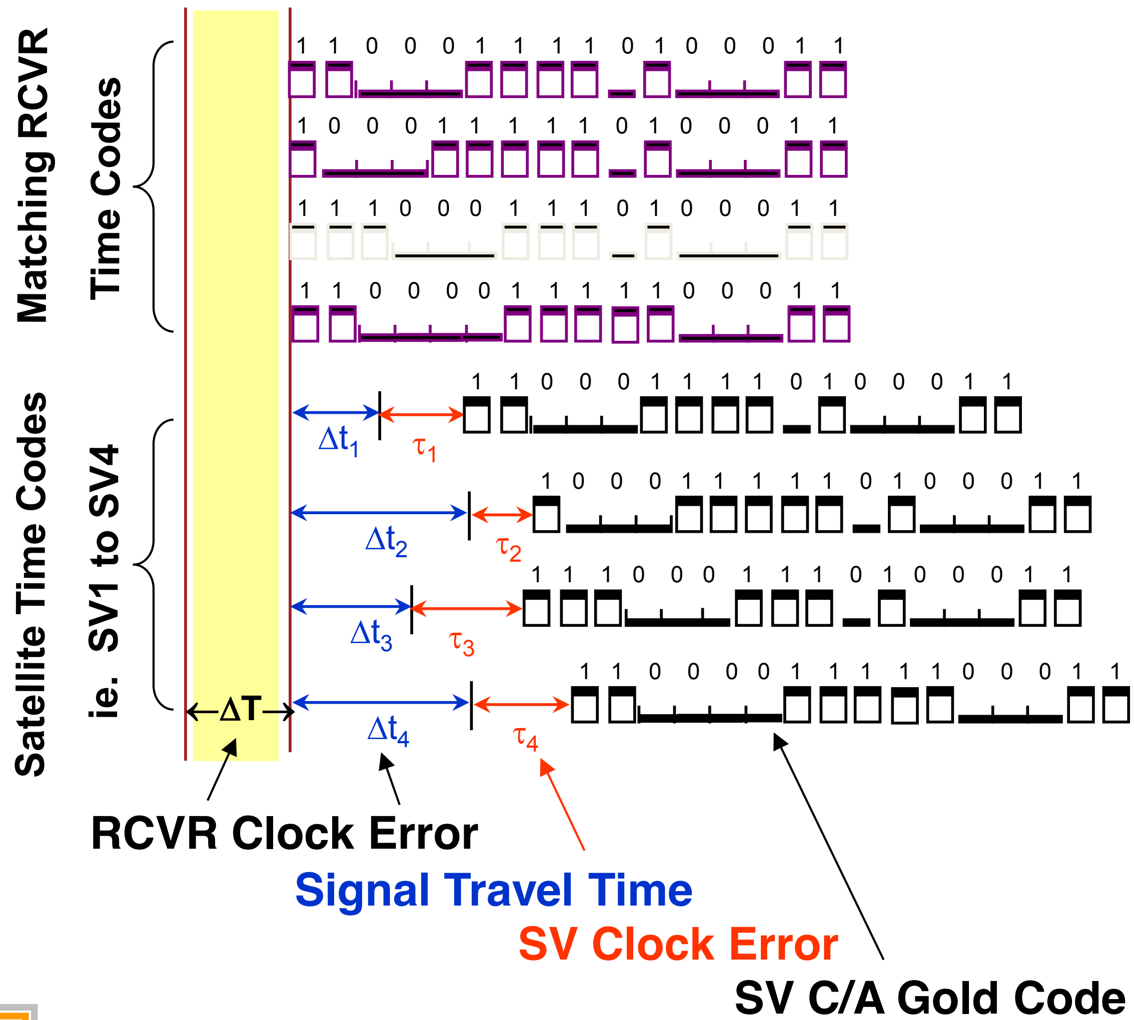


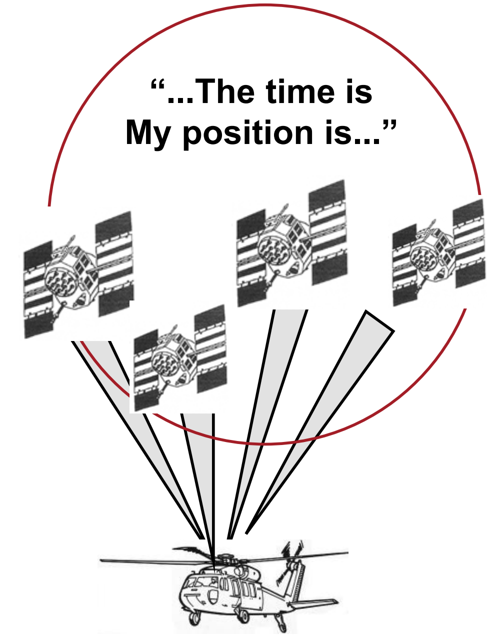
Note:

- **Black, Blue, Light Blue, & Dark Brown signals,** fully operational
- **Red and Purple signals,** only on a few GPS satellites
- **Dark & Light Green,** future Galileo signals (some Sats up now)
- **Yellow,** future Glonass signals
- **Light Brown**, future BeiDou (China Compass) signals (some Sats up)
- **White**, Future GPS-III signal

Space Borne Passive 3D Ranging

The Realistic GPS System





$R_1 = C(\Delta t_1 + \Delta T - \tau_1)$

$R_2 = C(\Delta t_2 + \Delta T - \tau_2)$

$R_3 = C(\Delta t_3 + \Delta T - \tau_3)$

$R_4 = C(\Delta t_4 + \Delta T - \tau_4)$

4 Equations — 4 Unknowns

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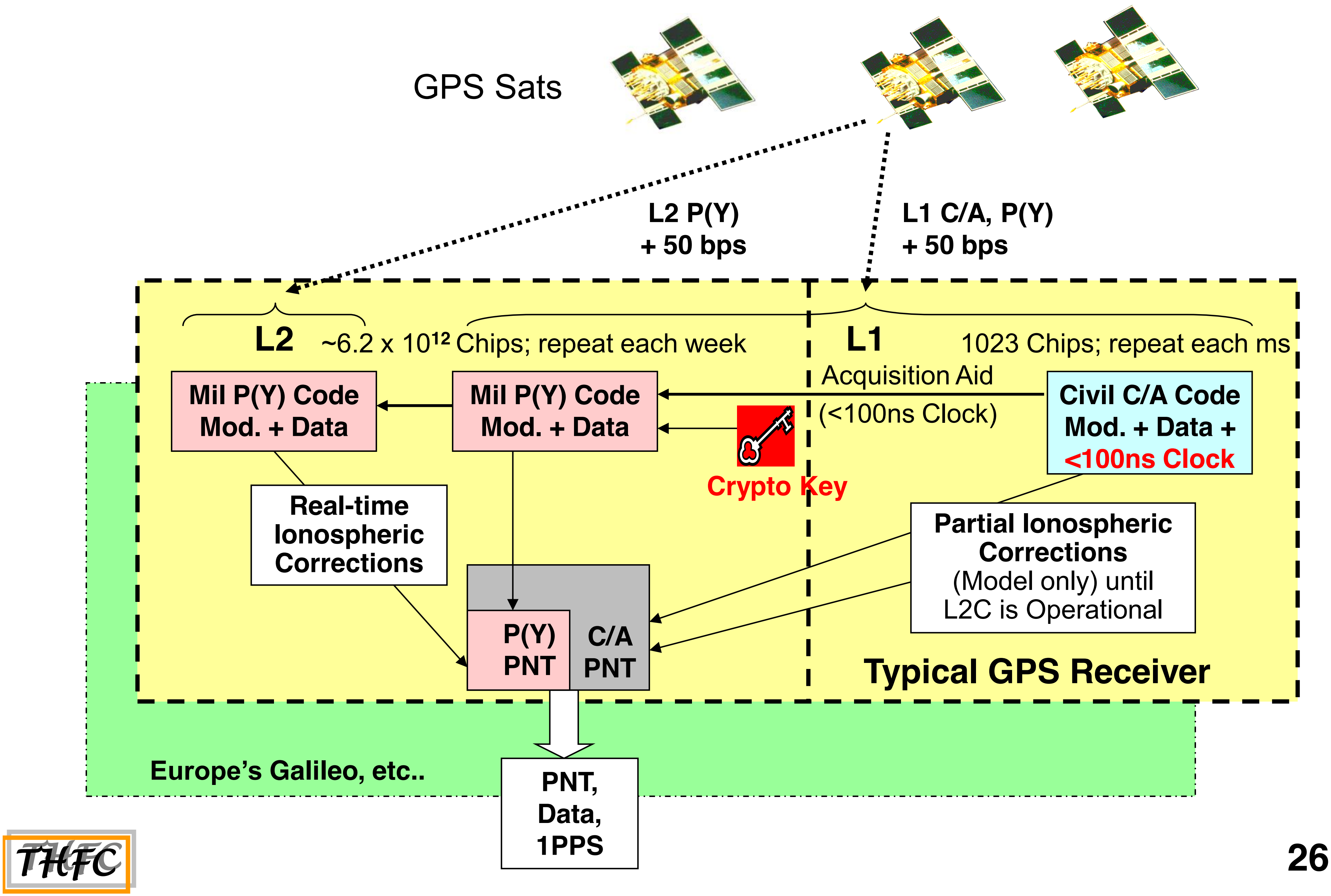
Civil and Military Signal Relationships



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- Commercial Mrkt
- Spoofing Problem

- 1st (4) Sat testing

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The Relativity Story

MAJOR GAYLORD GREEN. His innovations included design of the modified orbits that ensured daily test time at the instrumented Yuma range.

WALT MELTON, early leader of the Aerospace

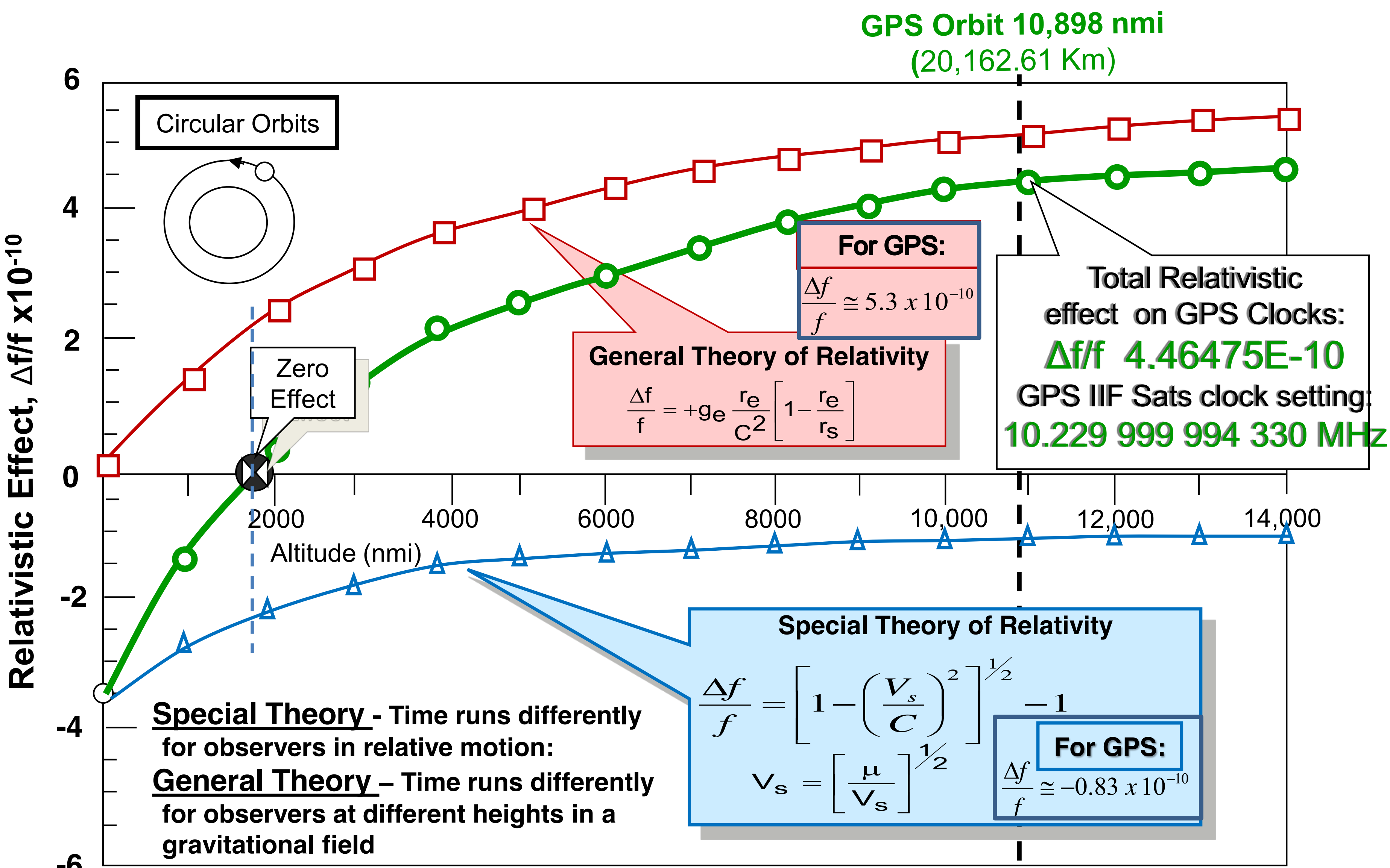
ED LASSITER was the Aerospace program manager under Brad Parkinson for the latter stages of Phase 1. A skilled engineer with much flight experience, he was especially skilled at early identification and solution to

DR. MALCOLM CURRIE. As the number 3 man in the Pentagon, his support was essential to overcoming resistance from the Air Force.

Government JPO Principal Engineer

Dr. Edward Teller, Lawrence Livermore National Laboratory, CA

Relativity & Clocks Frequency



$$\Delta t_r = t_{\substack{one\\day\\sec.}} * \frac{\Delta f}{f} = 86{,}400 * 4.46 \, x \, 10^{-10}$$

$$\Delta t_r = 38{,}621 \, \text{nsec}$$

~38.6 microseconds; about 7 mile error per day,

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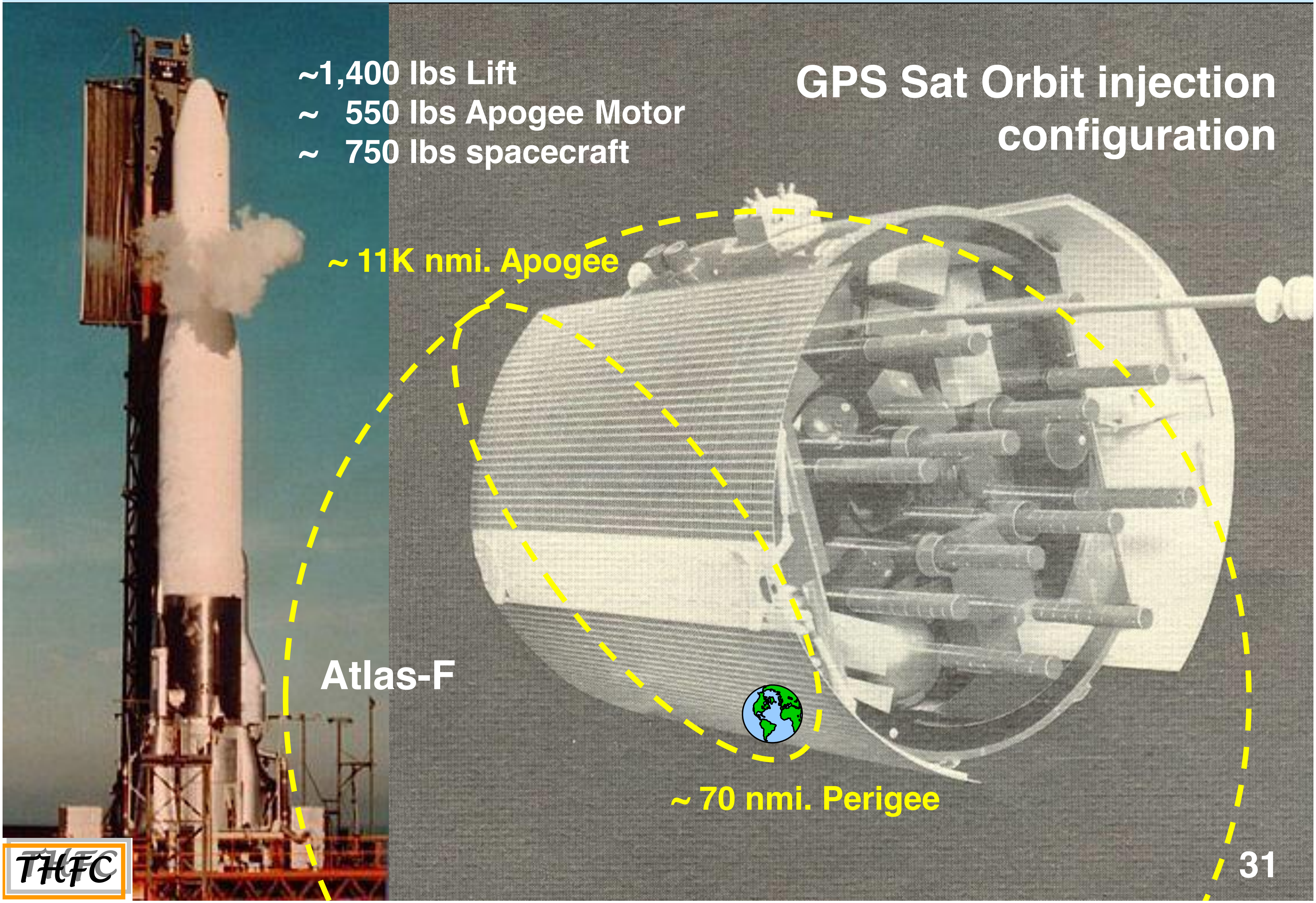
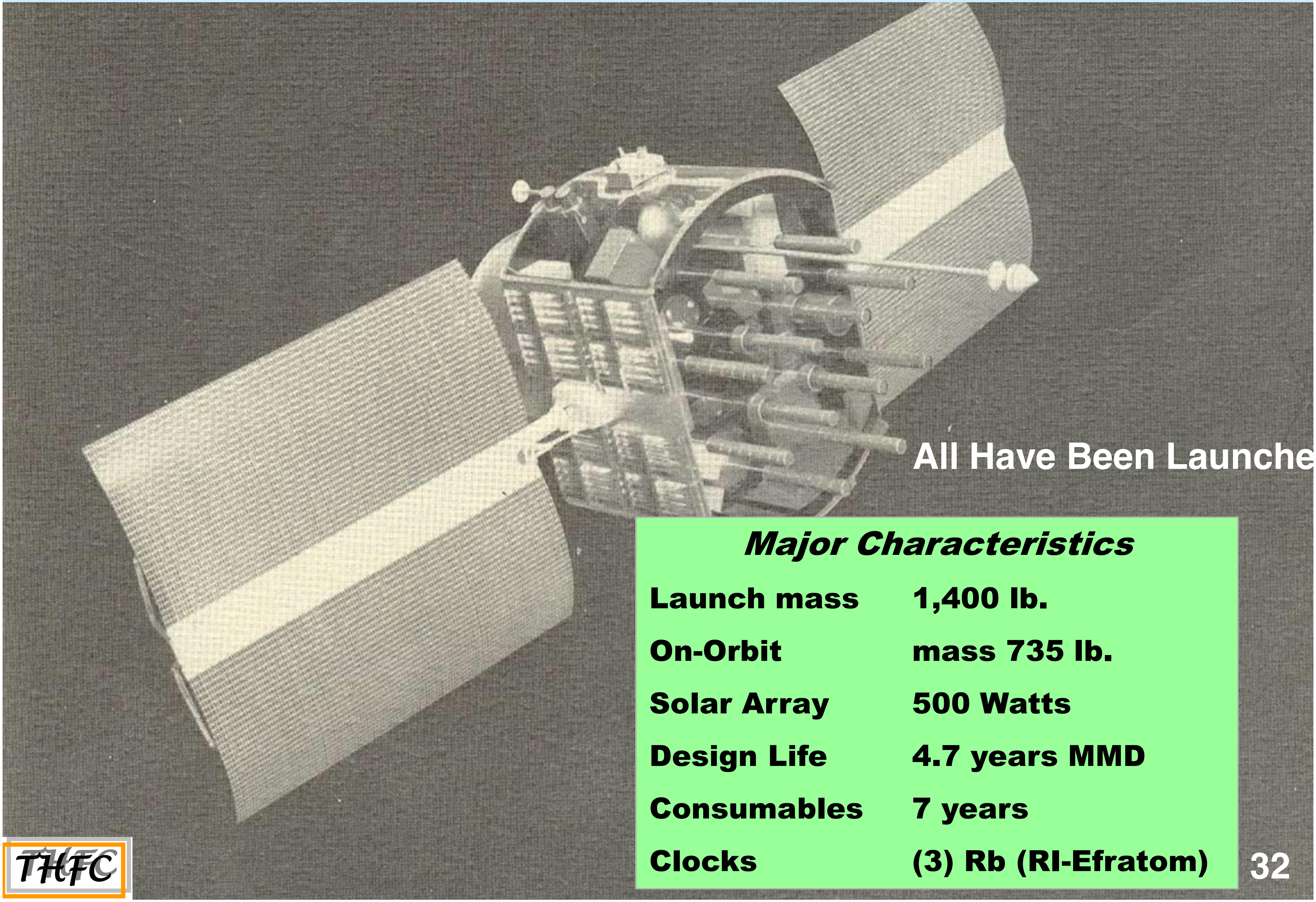
Initial Launches - Atlas-F's



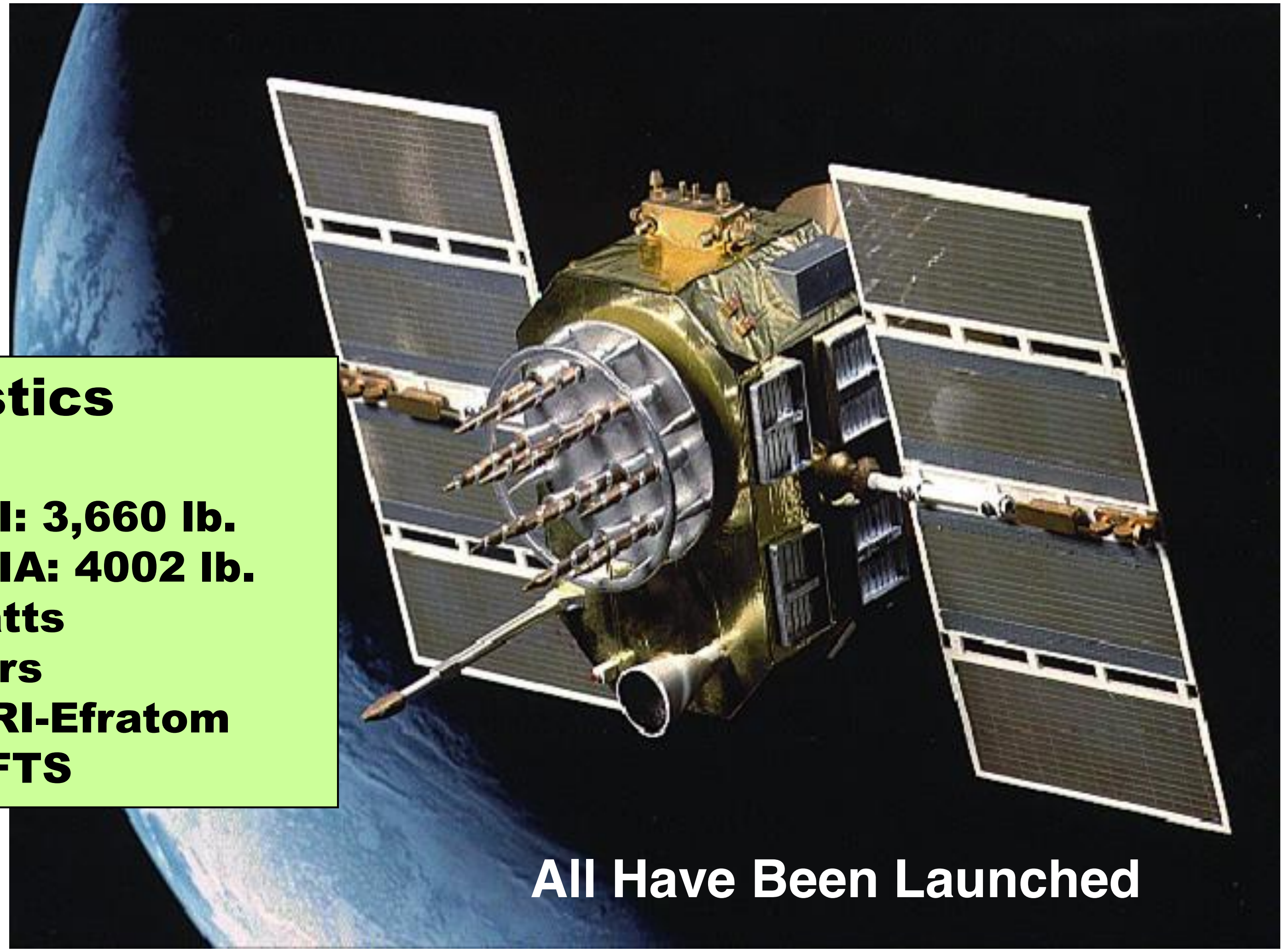
GPS Satellite (Block I) – Rockwell (RI)



Major Characteristics

Launch mass	**1,400 lb.**
On-Orbit	**mass 735 lb.**
Solar Array	**500 Watts**
Design Life	**4.7 years MMD**
Consumables	**7 years**
Clocks	**(3) Rb (RI-Efratom)**

GPS Satellite (Block II, IIA) Rockwell



Major Characteristics

Launch mass	Block II: 3,660 lb.
	Block IIA: 4002 lb.
Solar Array	710 Watts
Design Life	7.3 years
Clocks	(2) Rb RI-Efratom
	(2) Cs FTS

http://www.spaceandtech.com/spacedata/constellations/navstar-gps_consum.shtml
ftp://tycho.usno.navy.mil/pub/gps/gpsb2.txt

GPS Satellite (Block IIR) – LMSC

Major Characteristics

Launch mass	4,478 lb.
On-Orbit Wt	2.484 lb.
Solar Array	1,040 Watts
Design Life	7.5 years
Clocks*	(3) Rb Excelitas

All Have Been Launched

http://www.losangeles.af.mil/library/factsheets/factsheet.asp?id=18671
ftp://tycho.usno.navy.mil/pub/gps/gpsb2.txt

GPS Satellite (Block IIF) – Boeing*

* Was Rockwell International

Major Characteristics

Launch mass	4,634 lb.
On-Orbit Wt	3,230 lb.
Solar Array	1,900 Watts
Design Life	12 years
Clocks	(2) Rb Excelitas (1) Cs MicroSemi (Symmetricom)

In launch Phase

http://www.losangeles.af.mil/library/factsheets/factsheet.asp?id=18670

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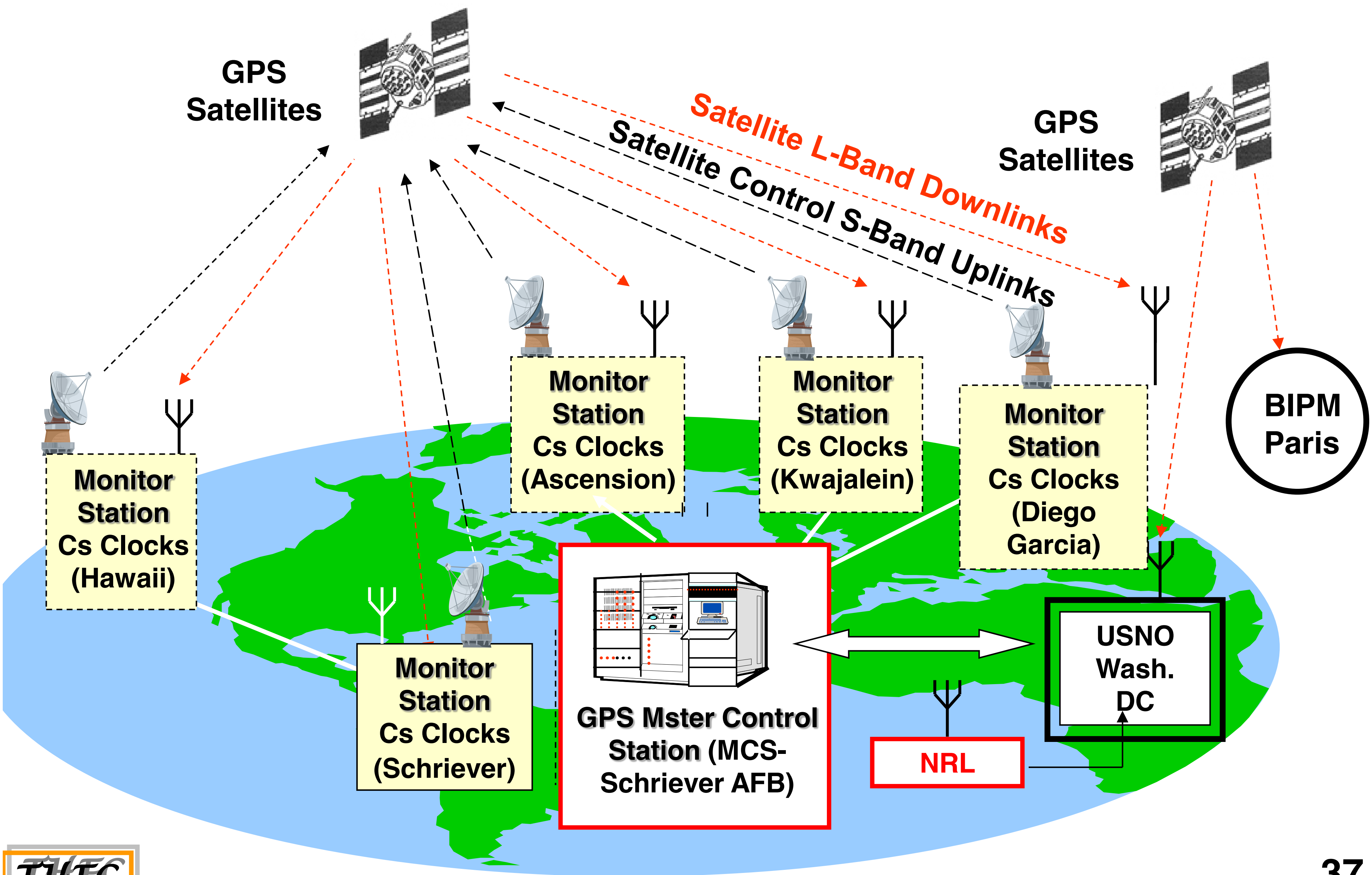
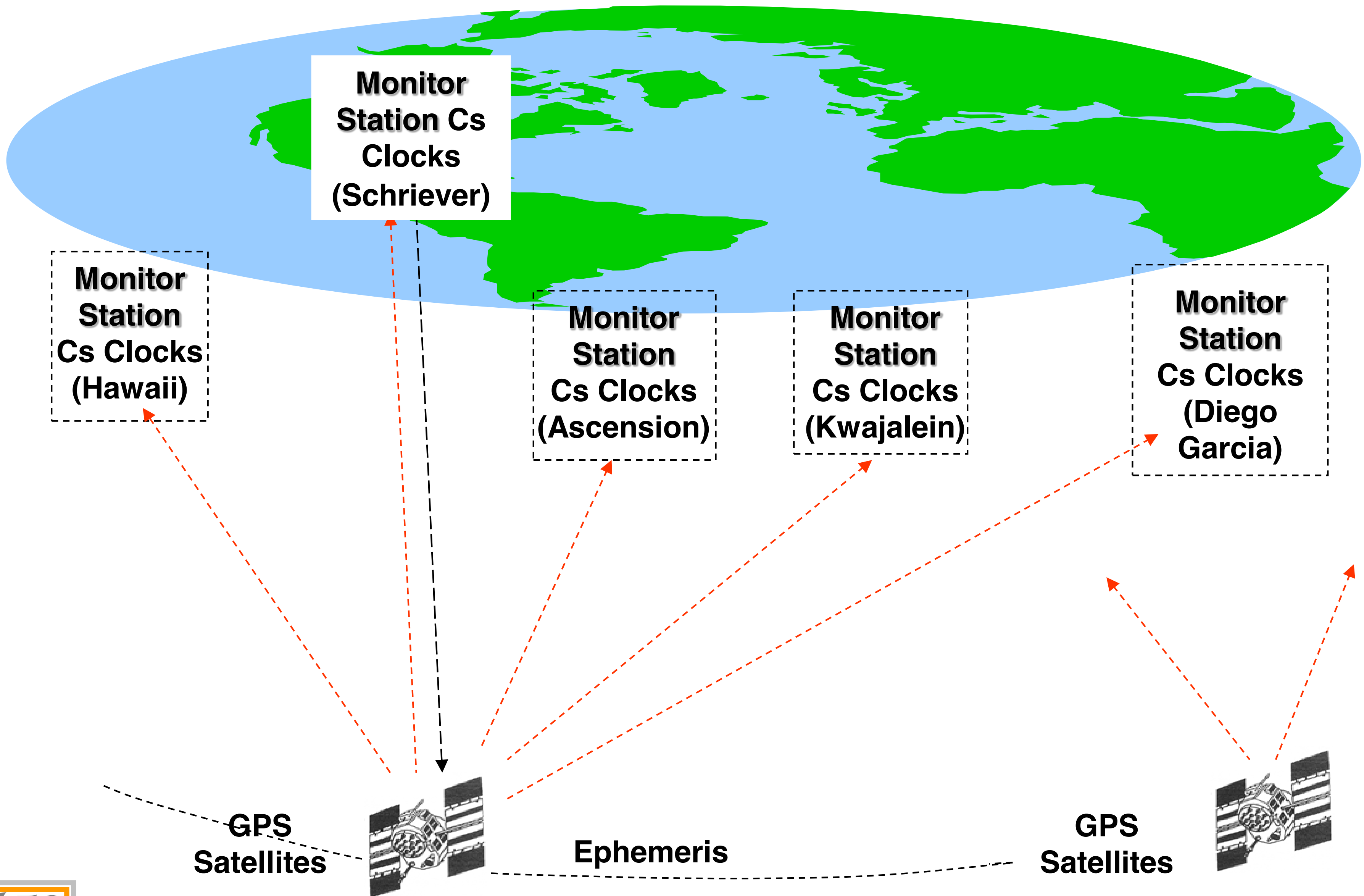
GPS Infrastructure



Extracting GPS Clock Error from Ephemeris (Sat Position) Error



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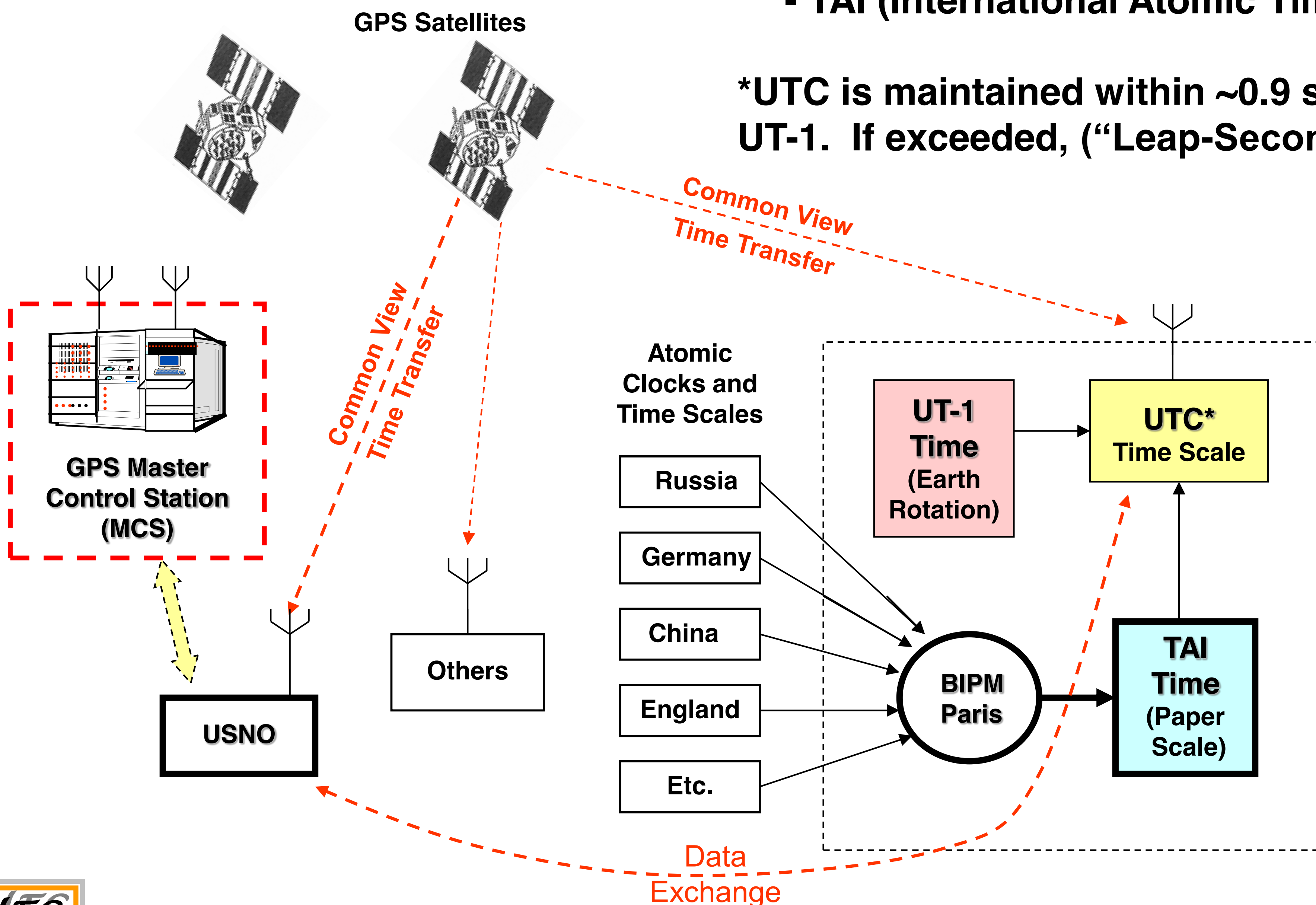
GPS Master Clock and BIPM

- BIPM (International Time Bureau)
  - TAI (International Atomic Time)

*UTC is maintained within ~0.9 sec. of UT-1. If exceeded, ("Leap-Second")



Precisian Targeting WW II (Best Guess, Hugo)

If precision bombing was available then to destroy Germany's war-related infrastructure:

~100 cities/target areas

(3) targets each area

(4) yrs of bombing, weekly

(1) ton bombs

(2σ) targeting accuracy

100 cities
x 3 targets
300
x 200 (4 yrs x 50 weeks)
~ 60,000 tons

Best guess Results:

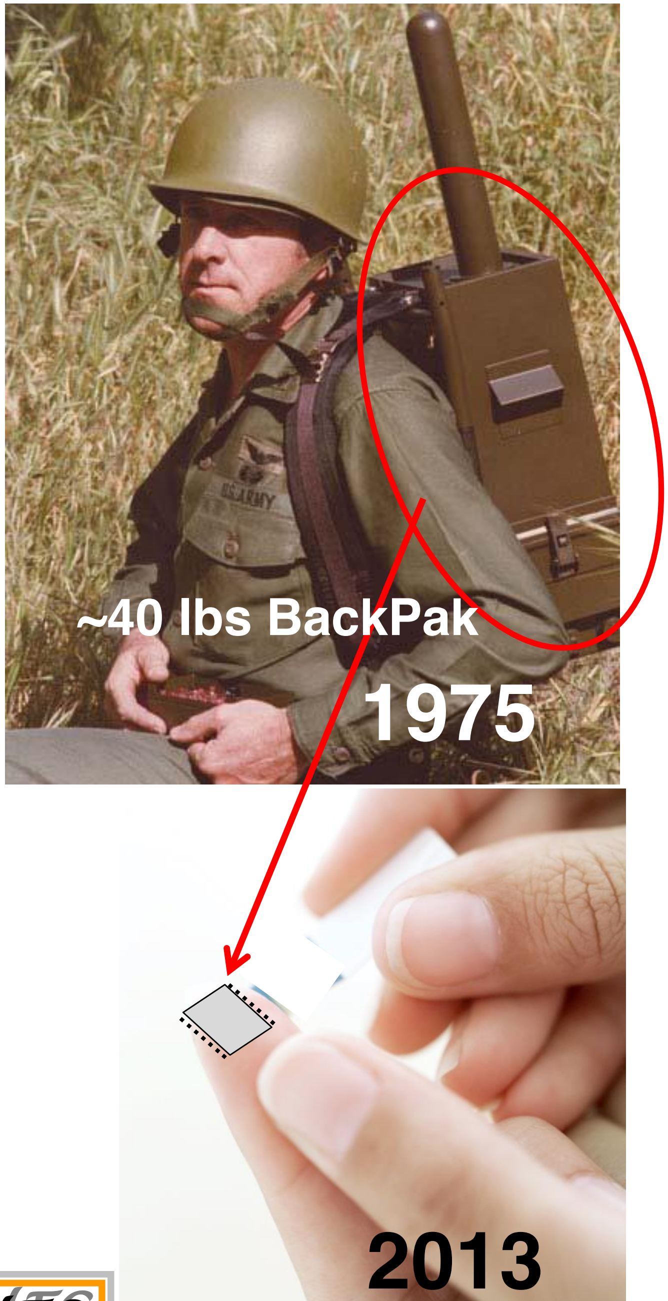
~95% of the targets destroyed

<5000 Civilian Casualties, **not ~600,000 to 1M**

~60K tons of bombs, not ~1.6M to 2M tons

THFC

GPS Receivers



GPS Navigation, Positioning, and UTC has become a global utility, along with:

- Water
- Energy
- Communications
- and Sanitation

GPS-related sales:

- 2013, $60B to $100B
- 2020, expect GPS/GNSS, >$1T

>1B Nav & Timing Rcvrs in use today (~7B global population)