Time Transfer in Space

Sir John Tenniel; *Alice's Adventures in Wonderland,* Lewis Carroll

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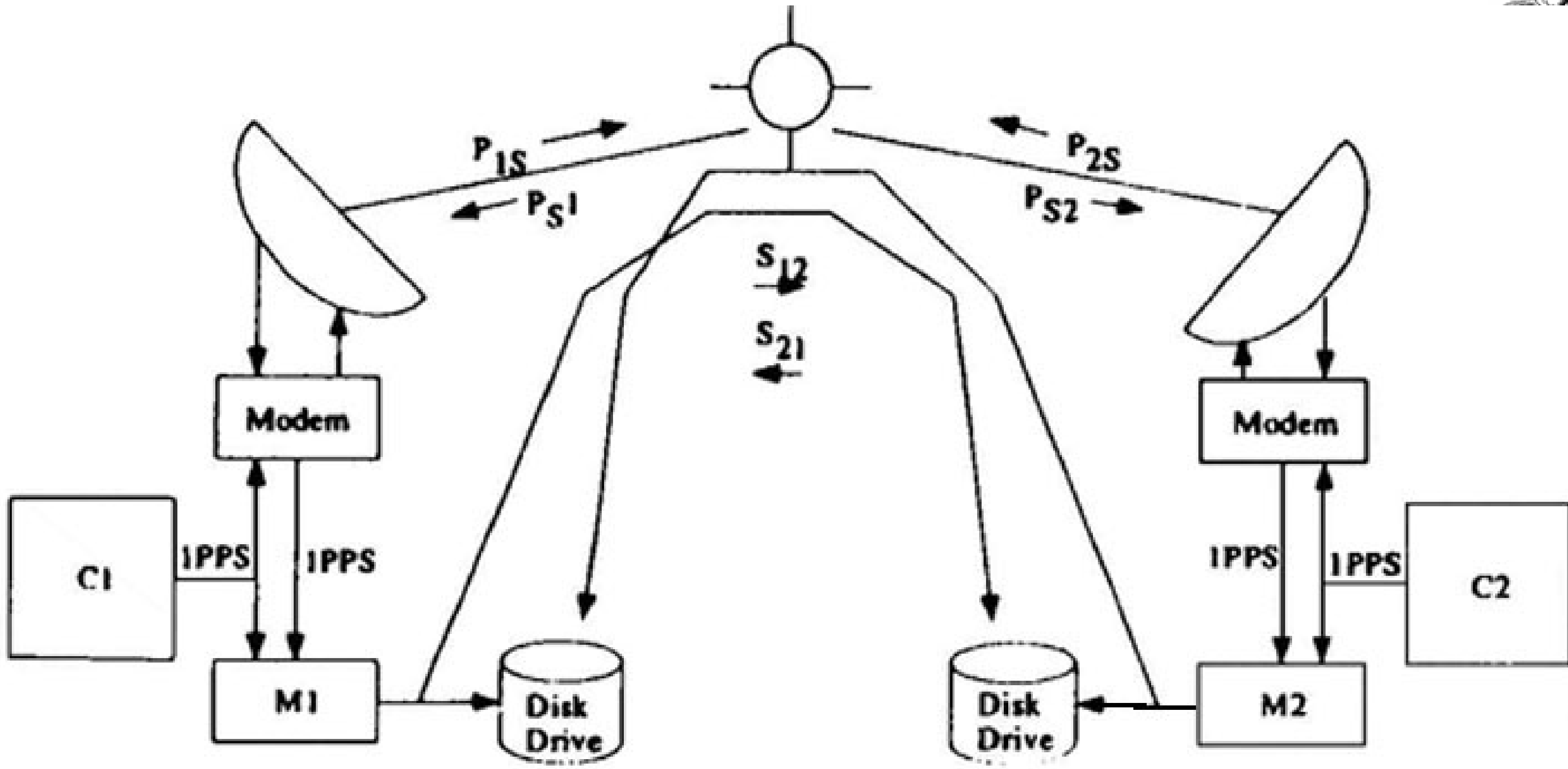
Experiments on NTP time transfer in space

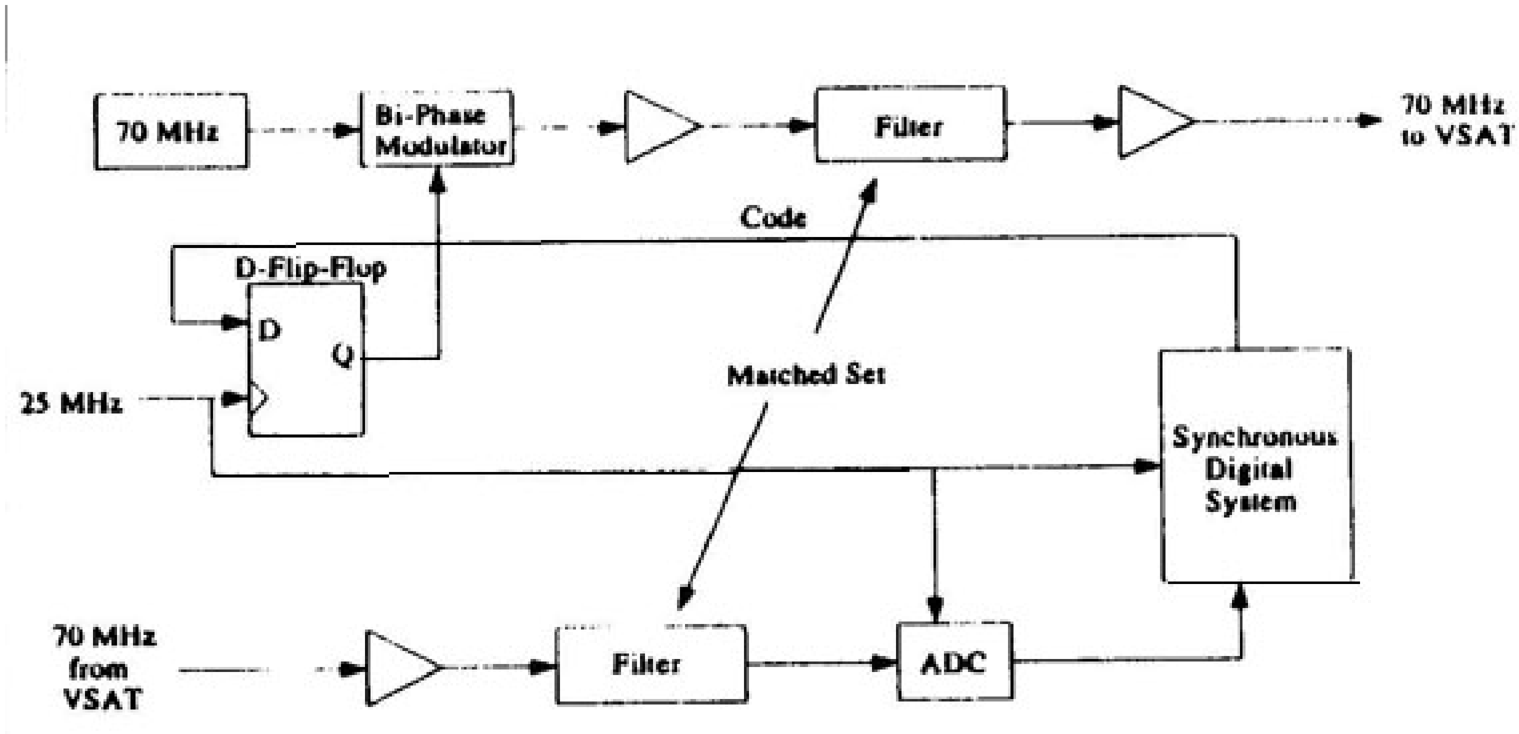
- There were many cases in the early NSFnet where NTP clocks were synchronized over satellite (VSAT) terminals. With two-way satellite links resutls were very satisfactory. However, results with mixed terrestrial/satellite links were generally unacceptable.
- In the early 1980s and again in 2000 there was an NTP time transfer experiment aboard an AMSAT Oscar spacecraft in low Earth orbit. The results showed little effects of satellite motion and Doppler.
- There was an NTP time transfer experiment aboard Shuttle mission ST-107 (Columbia). The results showed fair accuracy in the low millisecond range, but some disruptions due to laptop problems and operator fatigue.
- National Public Radio (NPR) now distributes program content and time synchronization via TCP/IP and NTP.
- The Constellation Moon exploration program is to use NTP.

Time transfer between stations on Earth via satellite

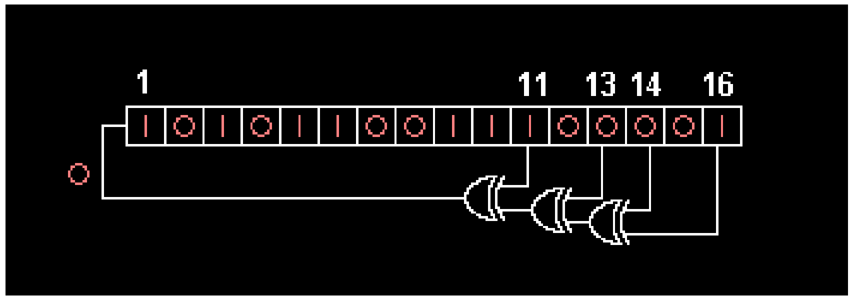


- Each station sends a pulse and starts its counter. It stops the counter when a pulse is received.
- Each station sends the counter value to the other station.
- The station clock offset is th difference between the counters.

70-MHz analog IF

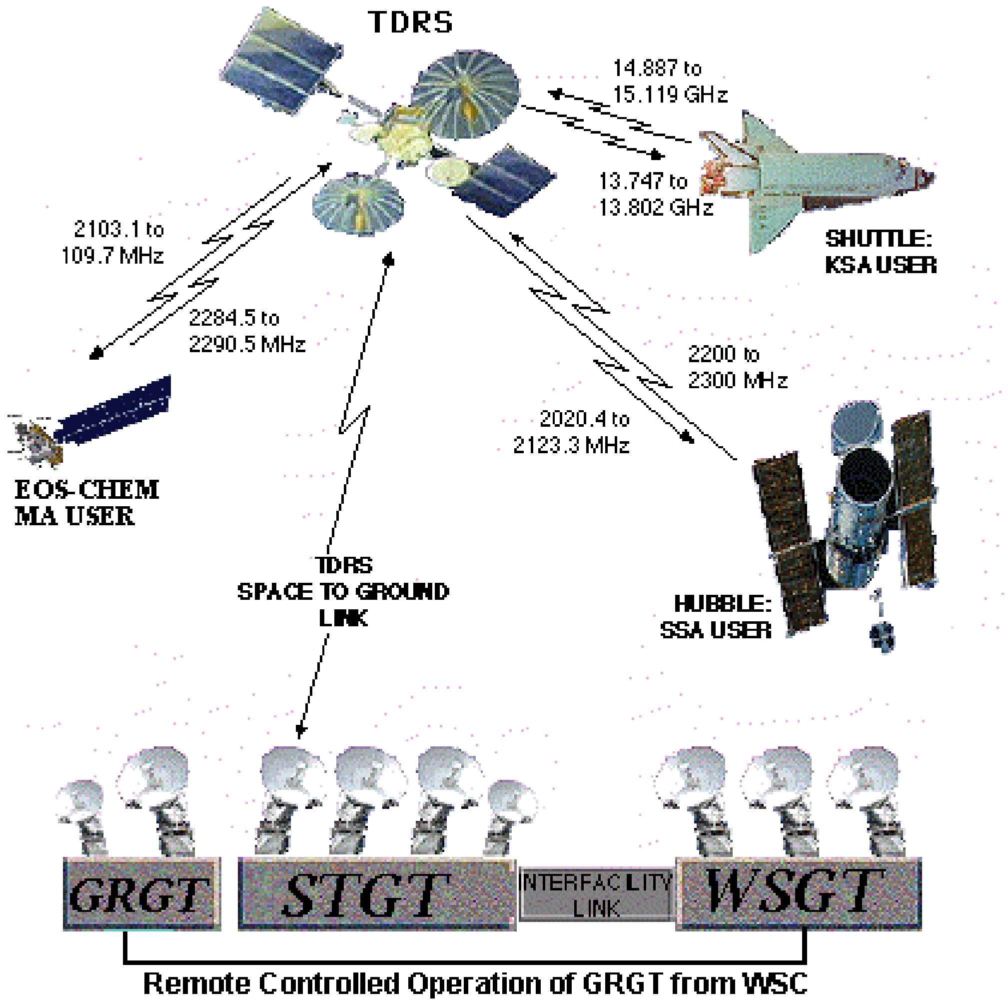


Linear feedback shift register generator

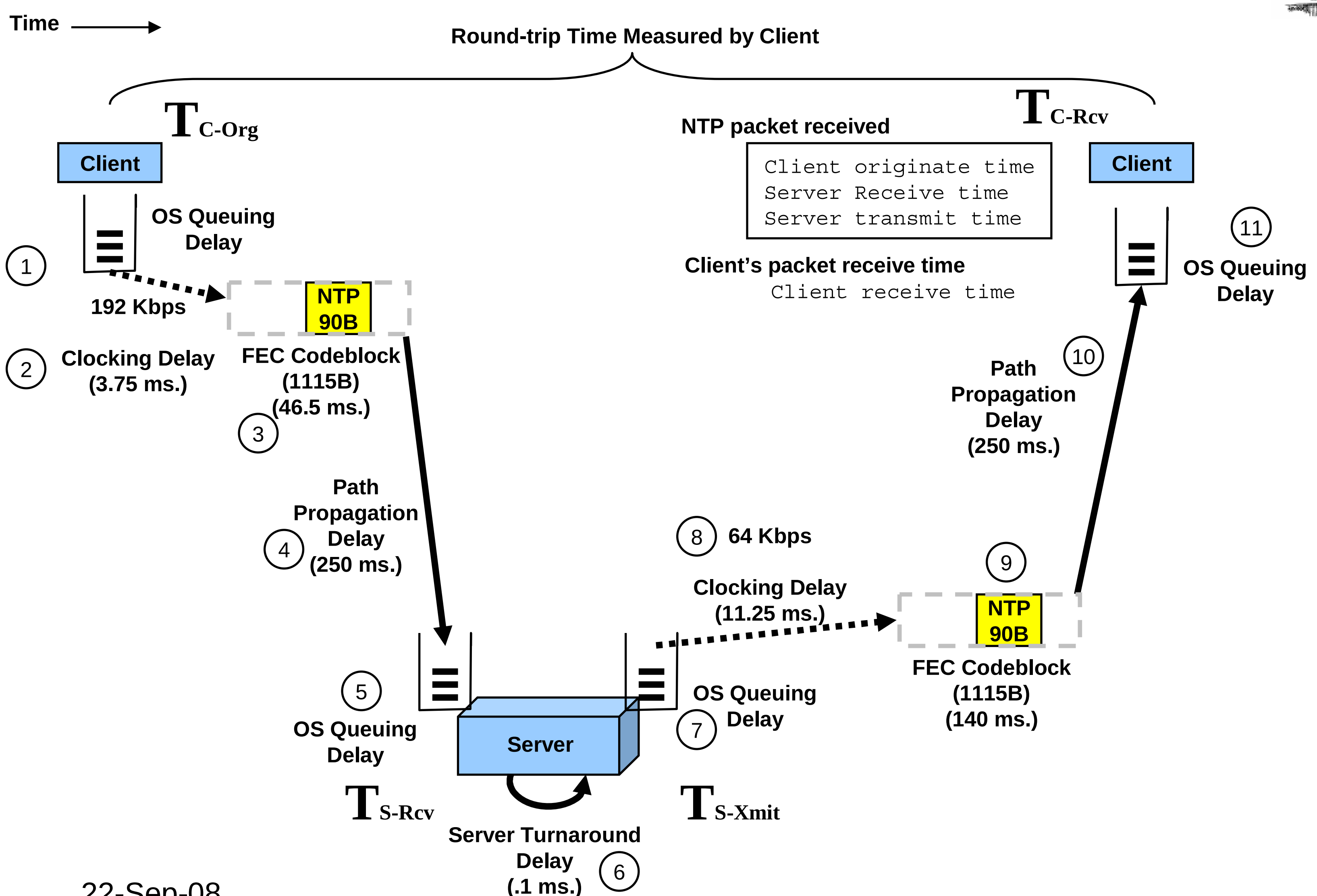


- The taps represent a primative polynomial over GF(2).
- It generates a binary sequence (chip) of 65535 bits with excellent autocorellation properties.
- The chips are modulated on a carrier in BPSK, one bit per chip and N bits per word. A one is an upright chip; a zero is an inverted chip.
- The chipping rate is chosen so that for some number M, MN is exactly one second.
- The first word in the second contains a unique code.

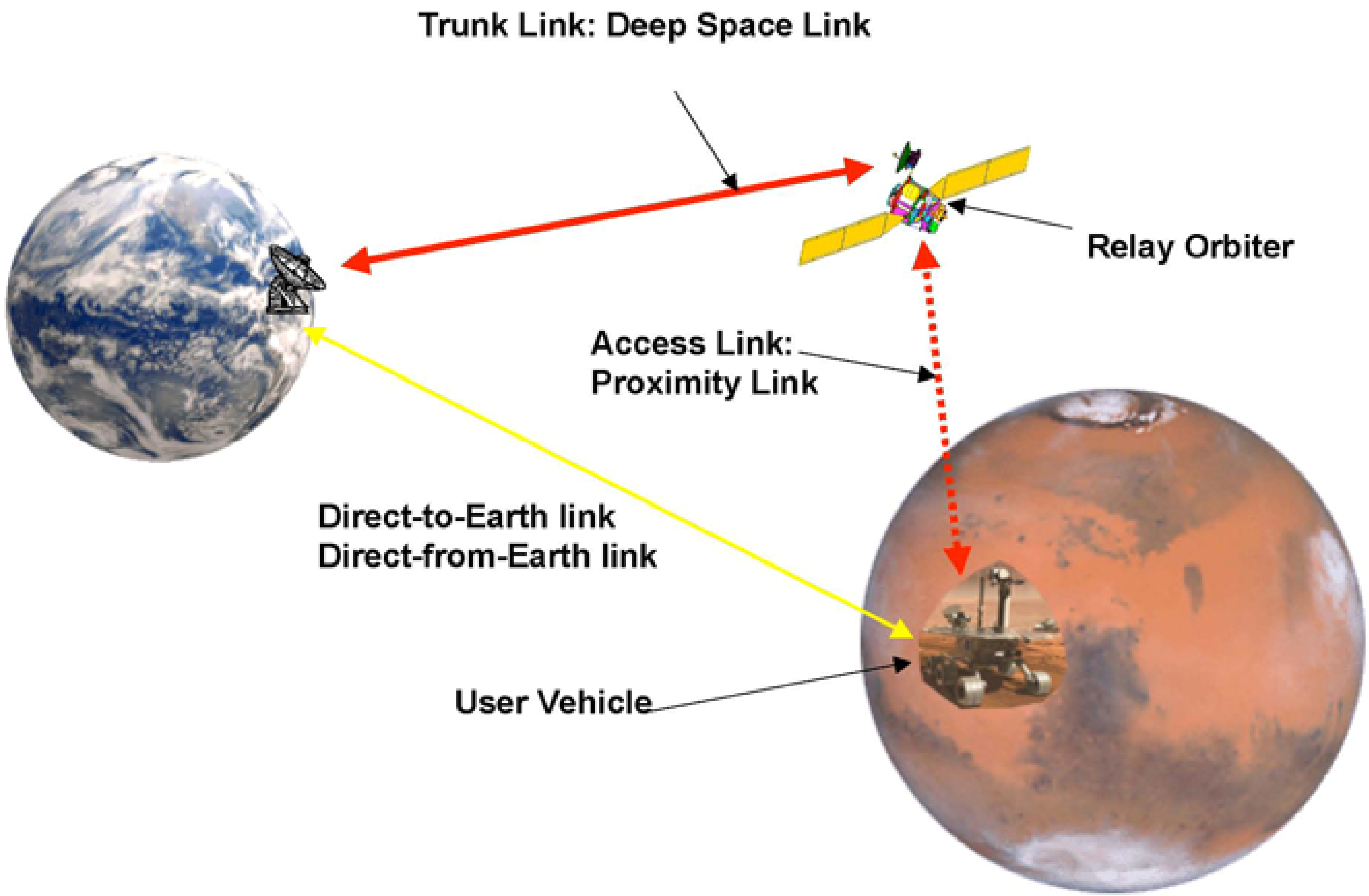
Time transfer to Shuttle via TDRSS



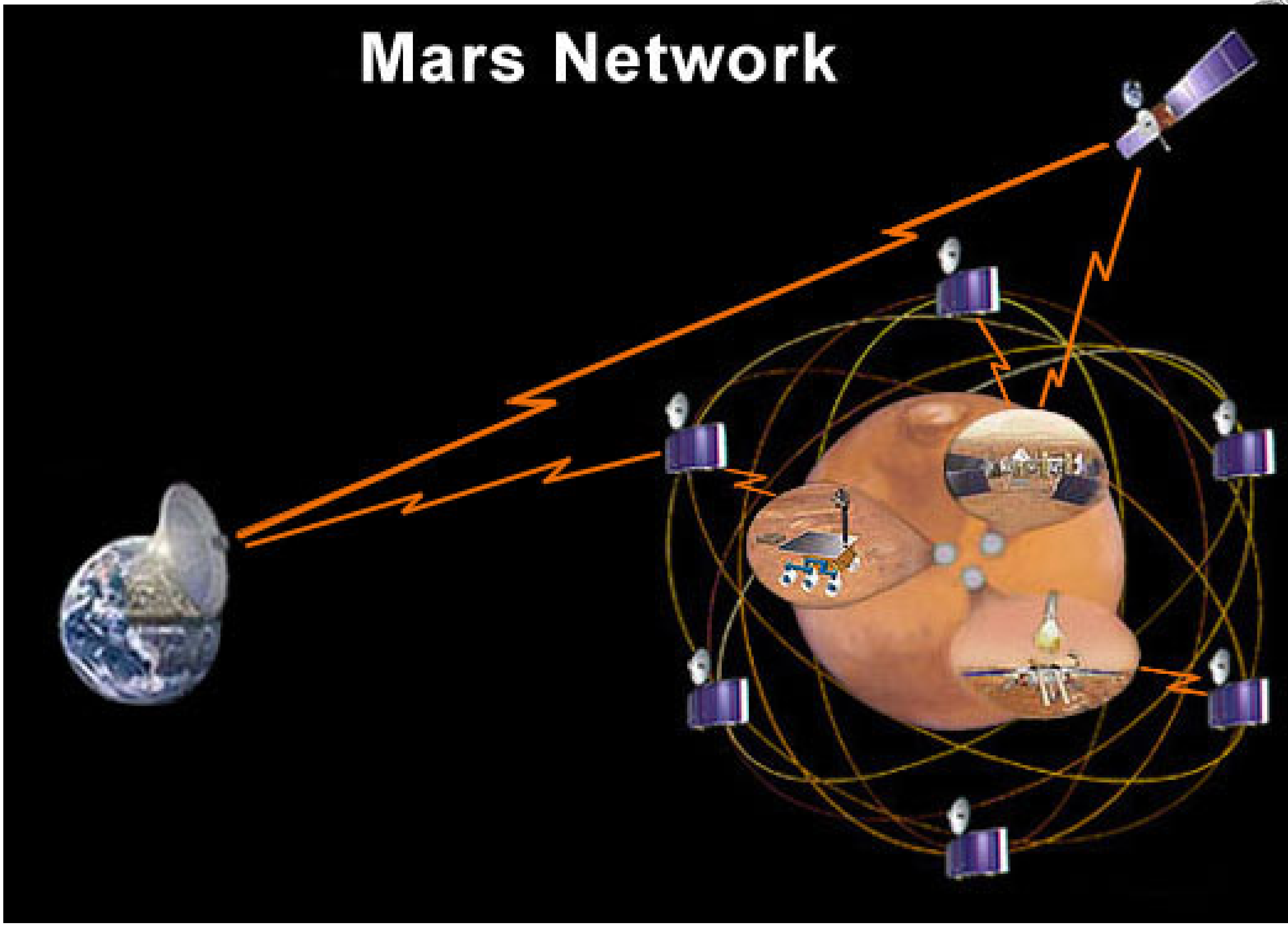
Time transfer to the Moon (simulation)



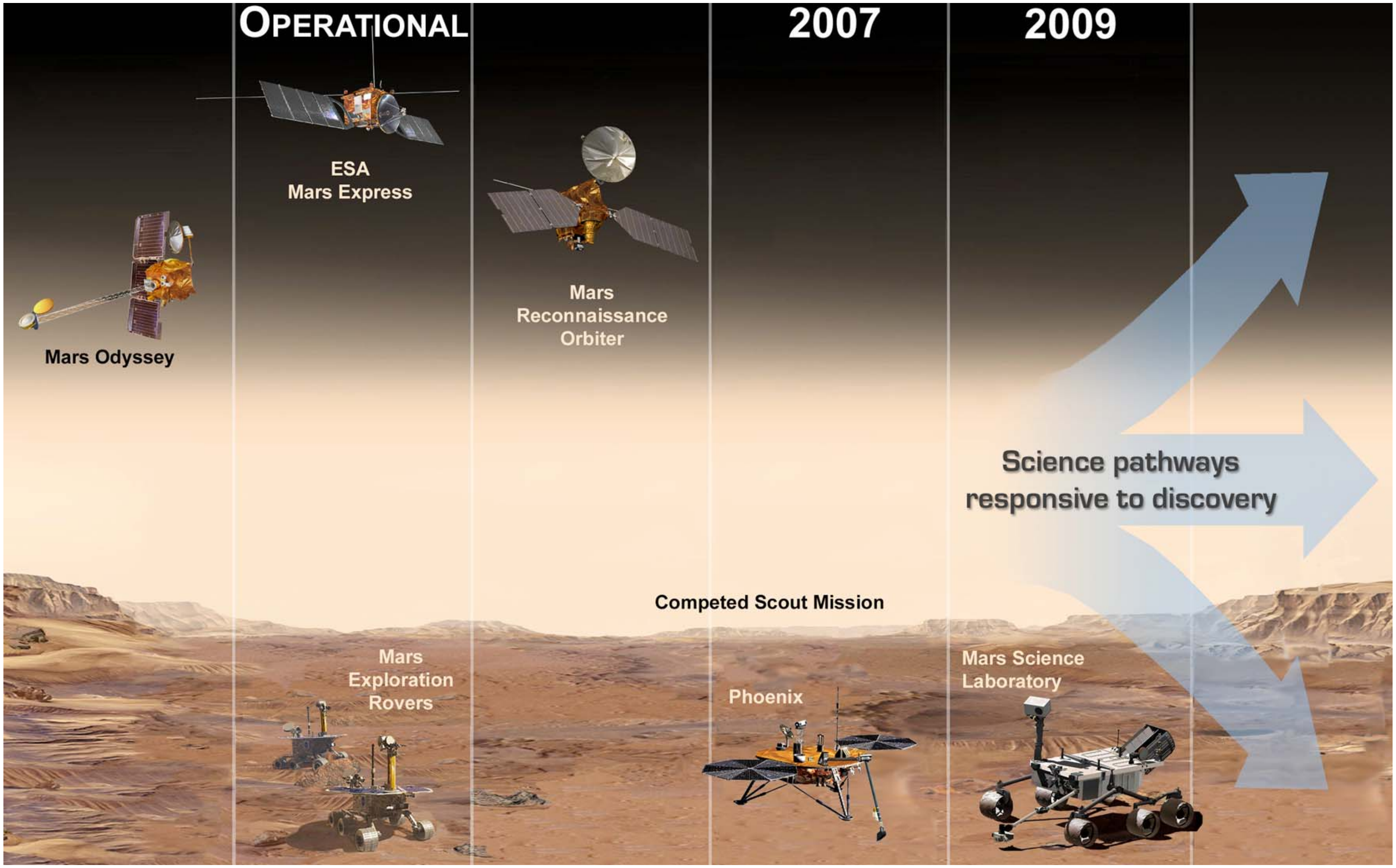
Time transfer from DSN to Mars orbiter



Solar system time transfer

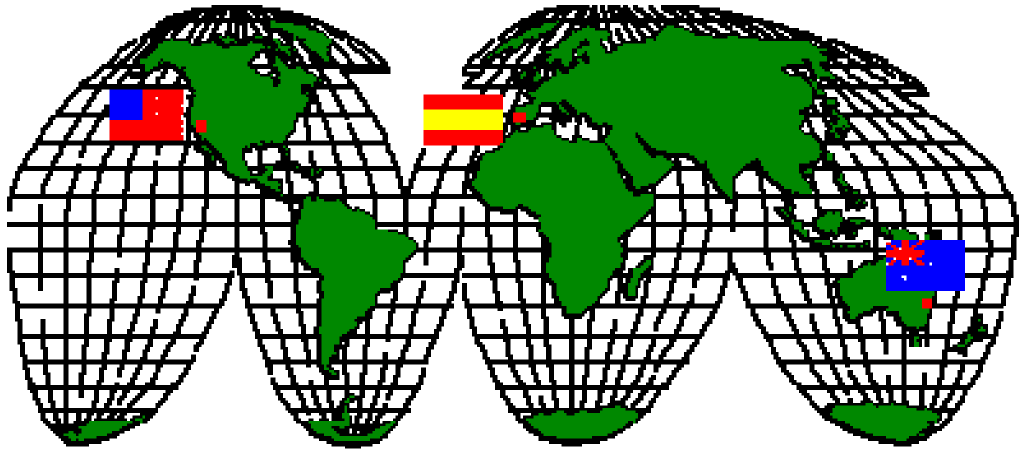


Mars orbiters and landers



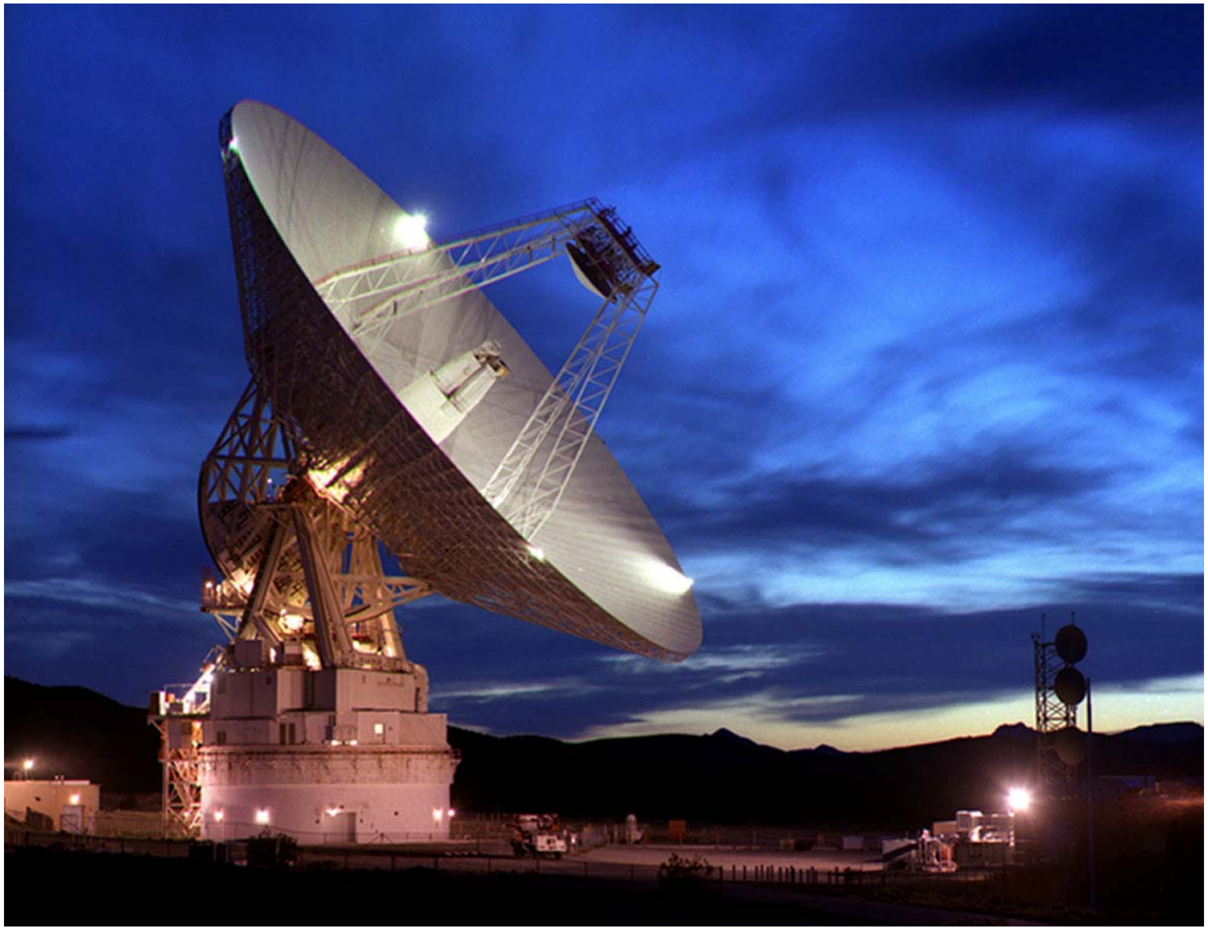
Mars exploration rovers (MER)

NASA/JPL deep space network (DSN)



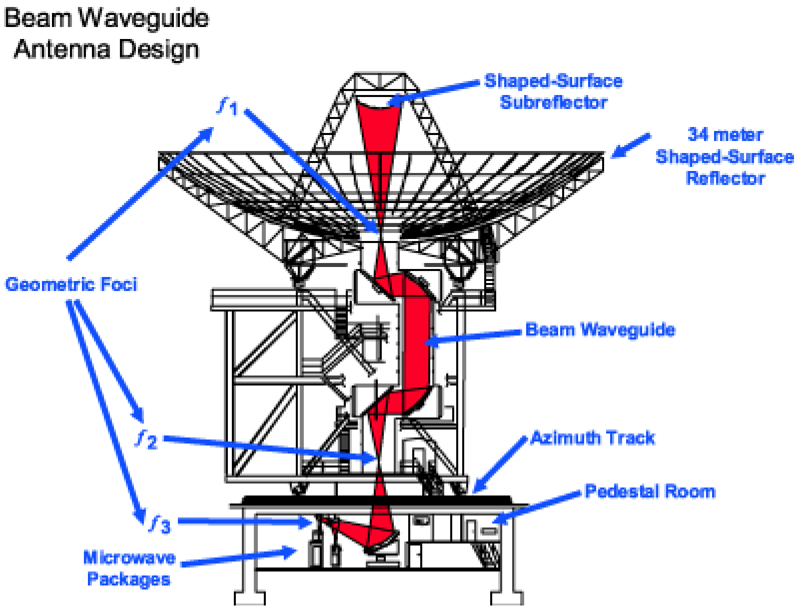
- DSN stations at Goldstone (CA), Madrid (Spain) and Canberra (Austrailia) controlled from JPL (Pasadena, CA).
- Appproximate 120-deg apart for continuous tracking and communicating via TDRSS.
- Antennas: 70-m parabolic (1), 34-m parabolic, (3-5), 12-m X-Y (2-3)
- Plans 12-m parabolic array (400).

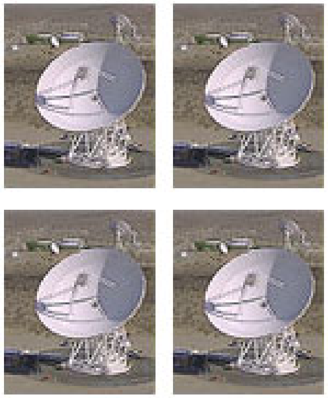
DSN 70-meter antenna at Ka band



- **P_o = 400 kW = 56 dBW Antenna: f = 32 GHz, D = 70 m; G = 82 dB**
- **ERP = 138 dBW or 7 TW!**

Other DSN antennas

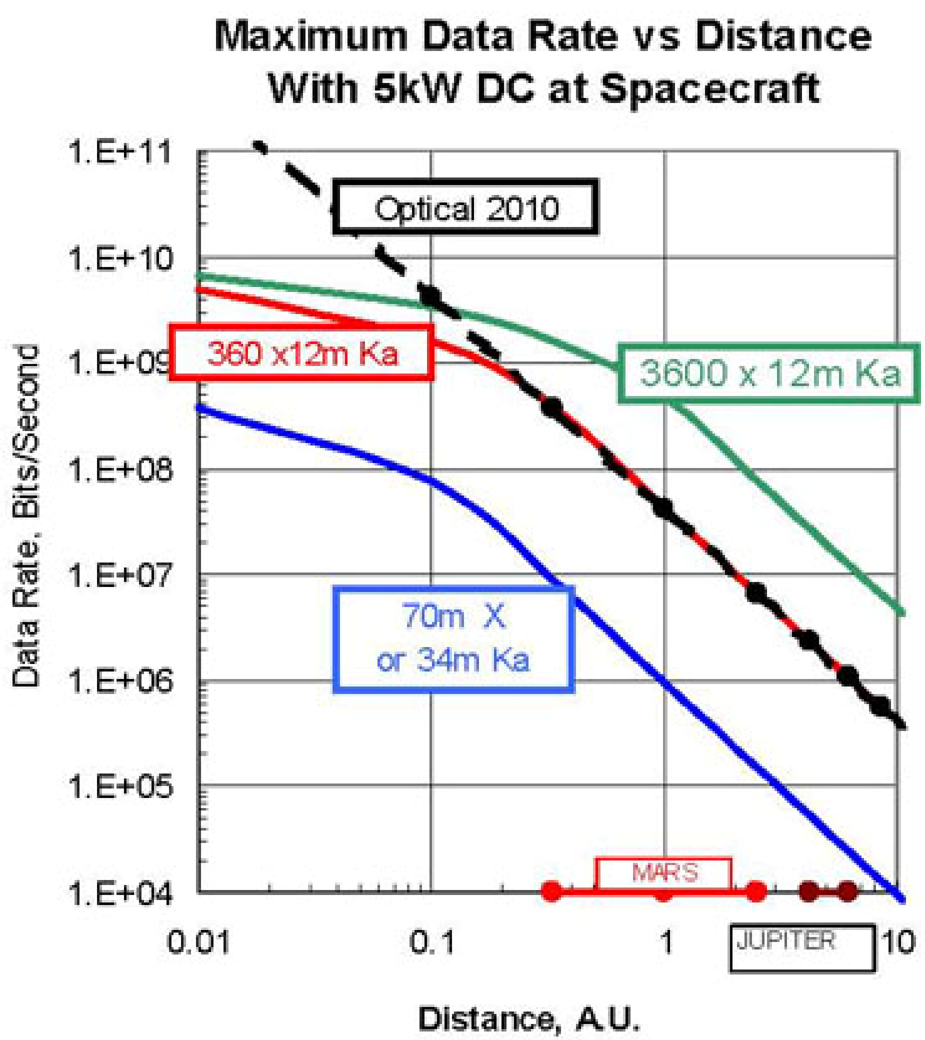




- 34-m enhanced beam waveguide antenna (EBWA).
- 0.1-10 Mbps Ka band at Mars
- Each station has three of these.

- Array of 360 12-m antennas.
- 10-500 Mbps Ka band at Mars
- Planned for all three stations.

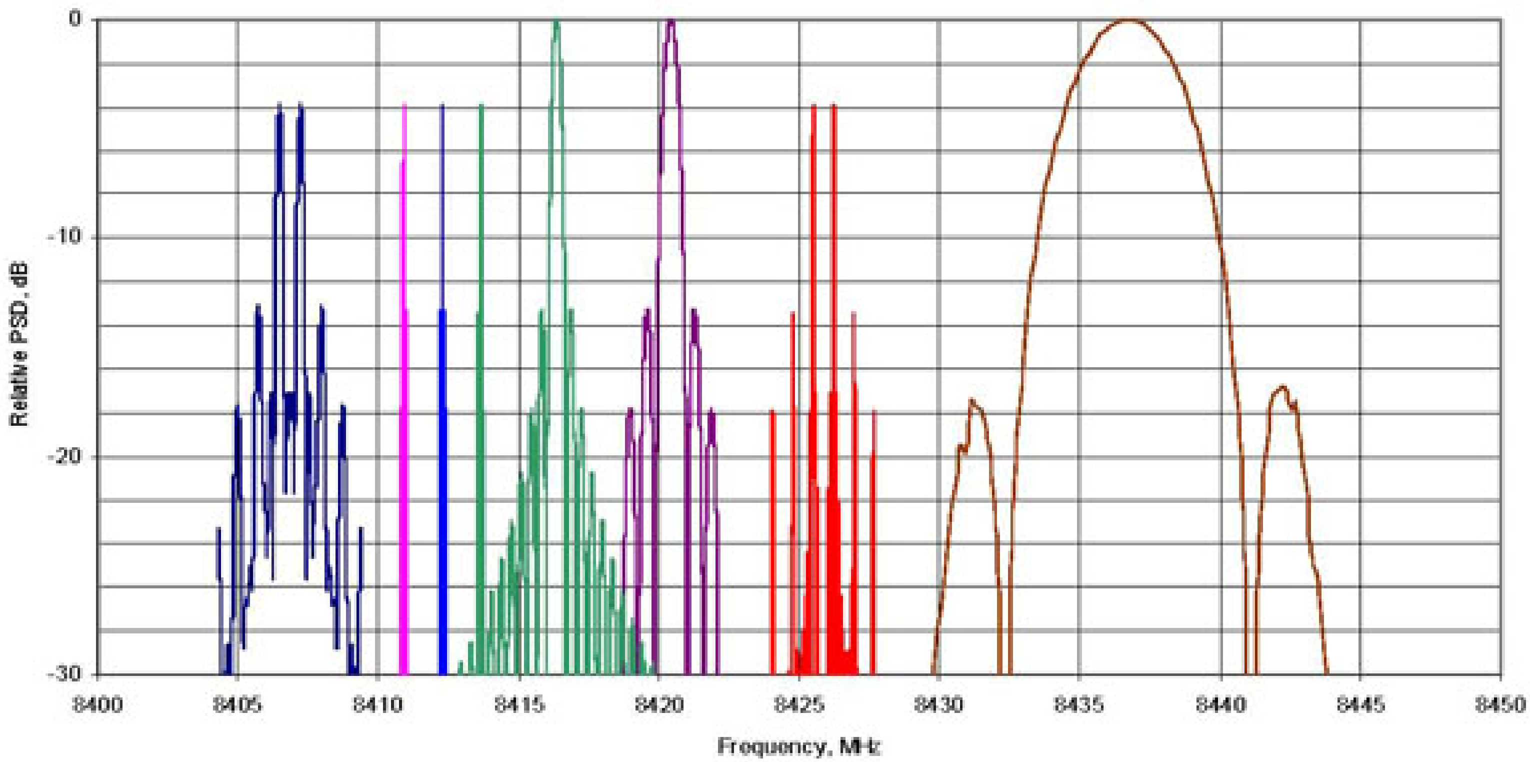
Downlink data rate



- UHF (Mars only)
  up 435-450 MHz
  down 390-405 MHz
  band 15 MHz
- S band
  up 2110-2120 MHz
  down 2290-2300 MHz
  band 10 MHz
- X band
  up 7145-7190 MHz
  down 8400-8450 MHz
  band 50 MHz
- Ka band
  up 34.2-34.7 GHz
  down 31.8-32.3 GHz
  band 500 MHz

Spectrum congestion at X band

Figure 1. Spectral Occupancy of Mars Missions in 2007 Time Frame (Data rates are as currently conceived by missions)



-Only Mars Express and Odyssey have been assigned a frequency channel

-The center frequency (downlink) of the *n th* channel is given by

*8400.06 + (n-3)*1.36 MHz*

Odyssey(220ksps, ch.8)
Mars07Landerr (7.2 ksps)
Mars07Rover (7.2 ksps)
Mars Scout Orbiter(9 ksps)
ME(586 ksps, ch.18)
CNES07Orbiter(60 ksps)
Telesat(360 ksps)
Mars05(4.4Msps, filtered)

The devil is in the details

- Proper time: time measured on the suface or in orbit about a primary body.
- Barycentri time: time measured at the point of zero gravity of the orbiter and primary body.
- Time is transferred from GPS orbit to Earth surface, then via Earth barycenter, solar system barycenter, Mars barycenter and proper time at Mars orbiter.
- The calculations may need systematic corrections for
  - Gravitional potential (red shift)
  - Velocity (time dilation)
  - Sagnac effect (rotating frame of reference)
  - Ionospheric corrections (frequency dependent)

Coordinate conversions

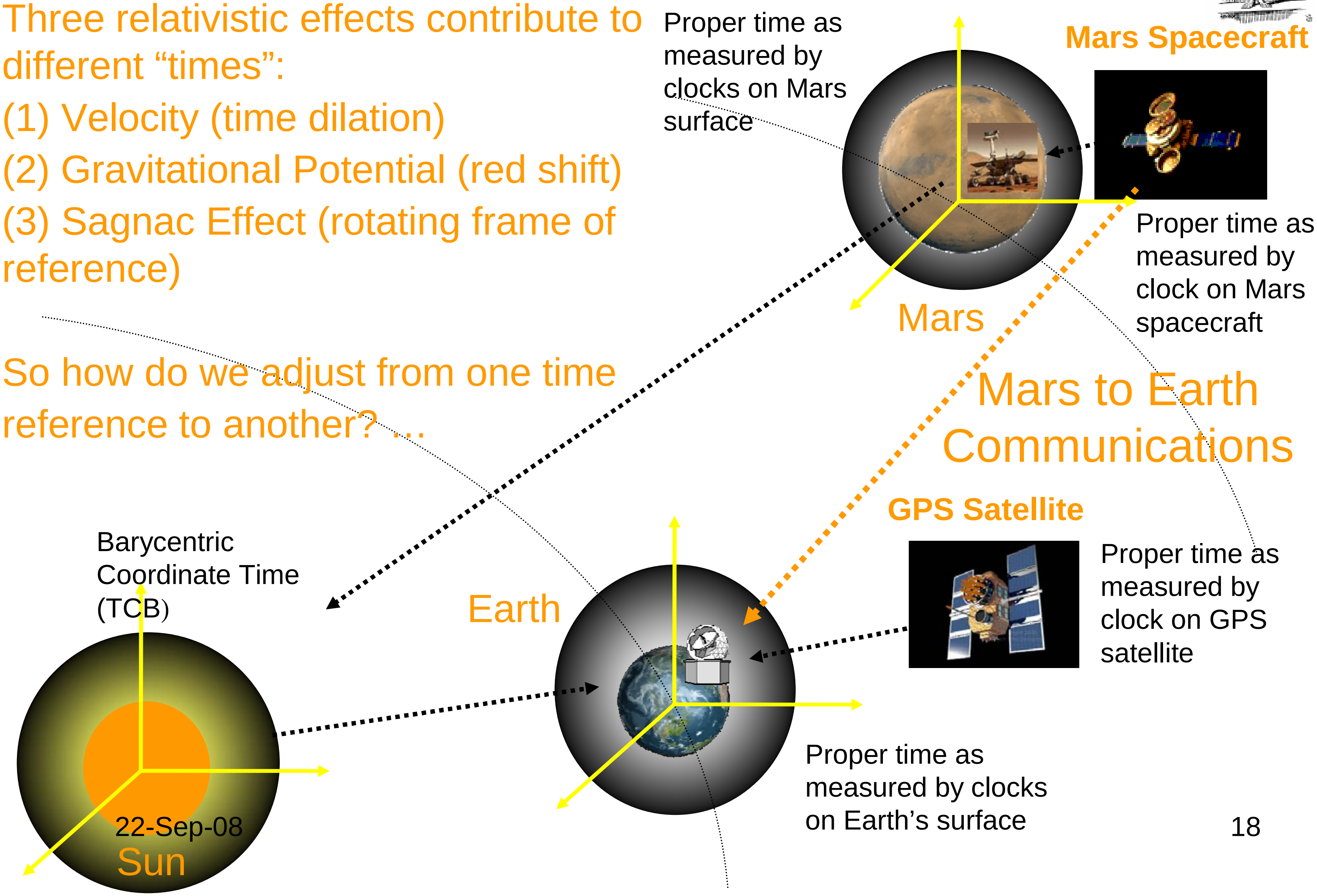
Three relativistic effects contribute to different “times”:

(1) Velocity (time dilation)

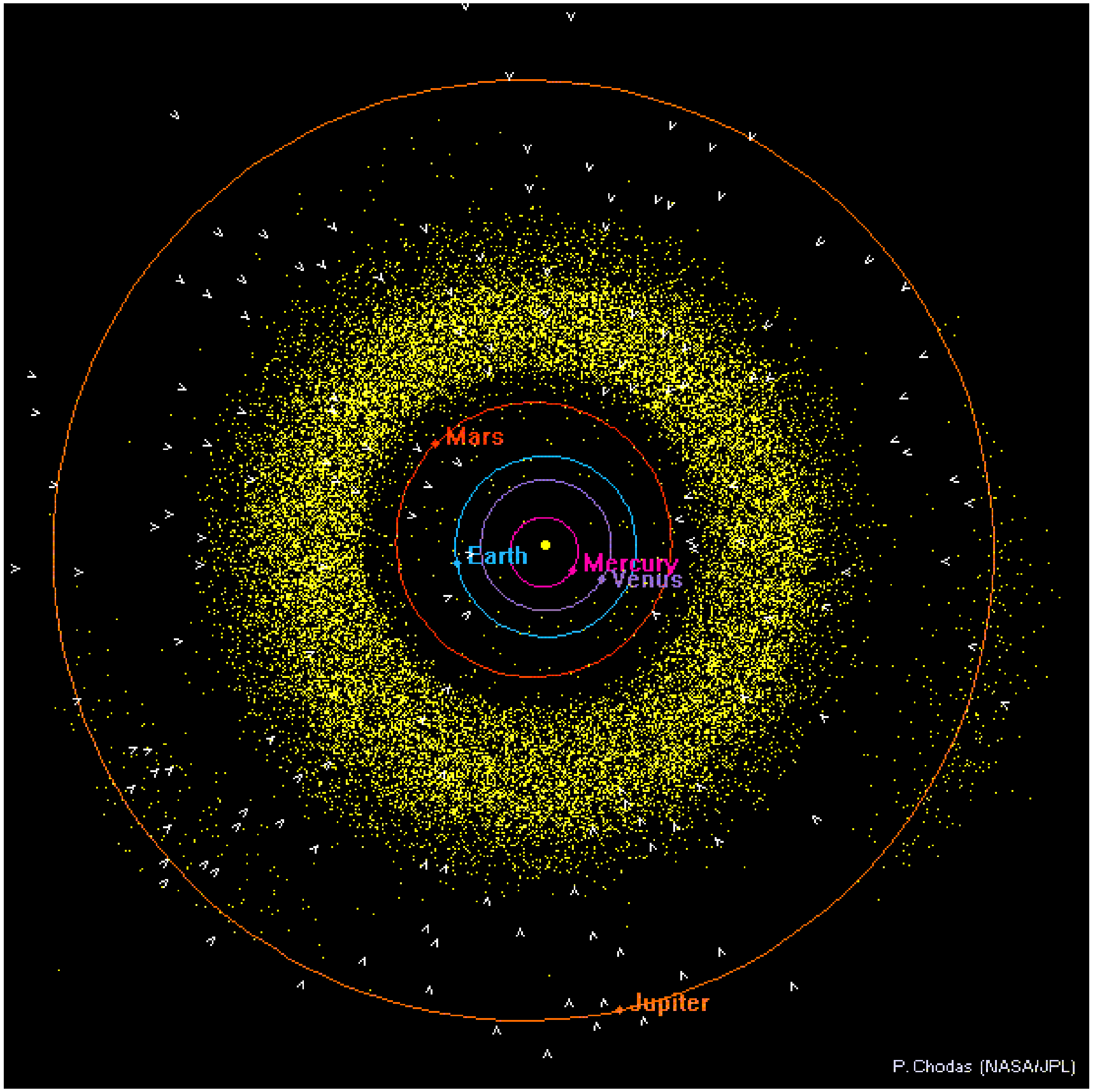
(2) Gravitational Potential (red shift)

(3) Sagnac Effect (rotating frame of reference)

So how do we adjust from one time reference to another? …

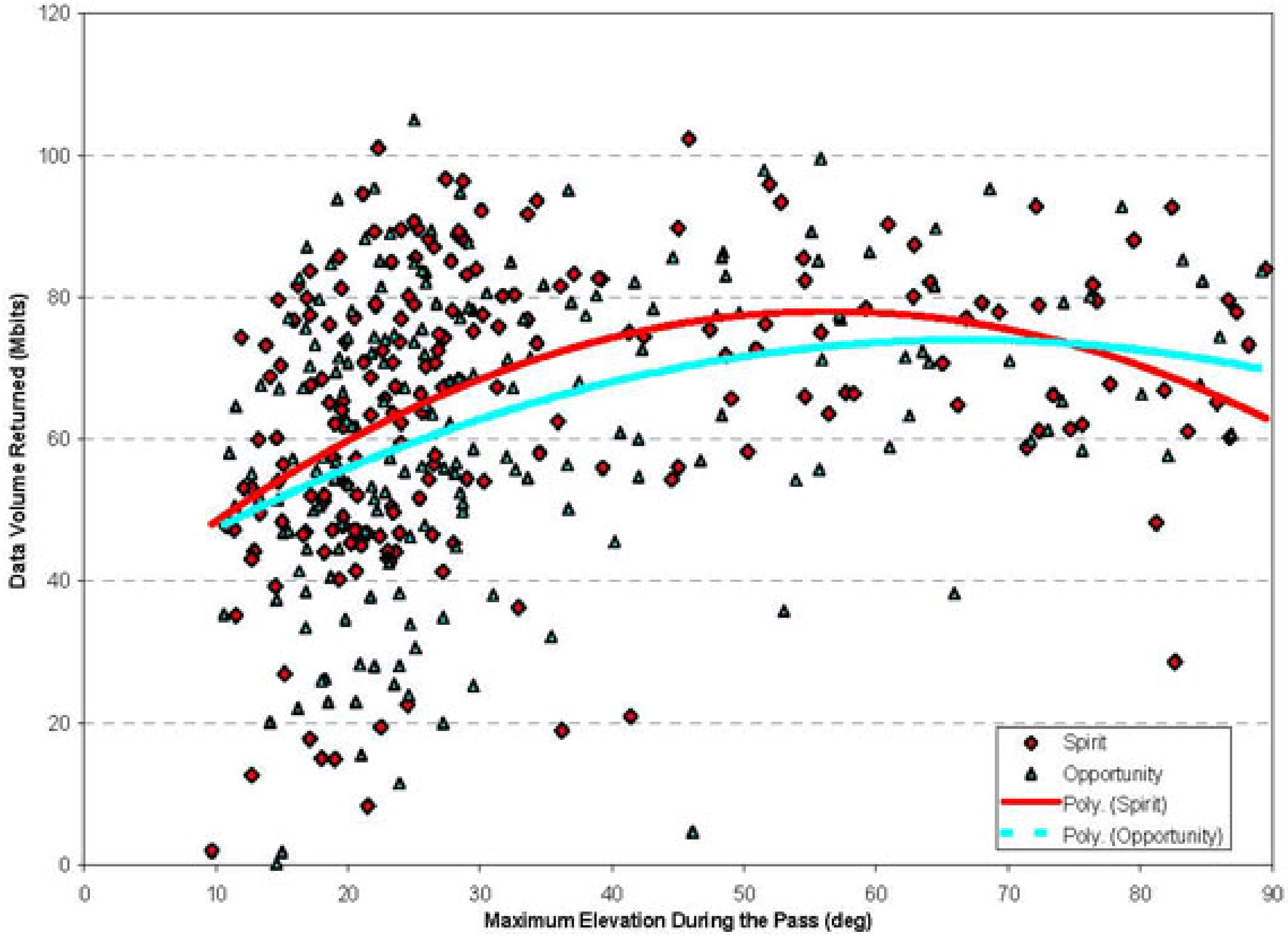


Inner planet orbits



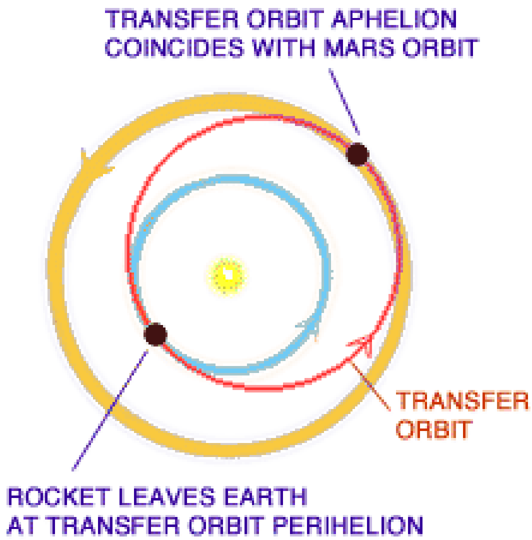
Facts of life

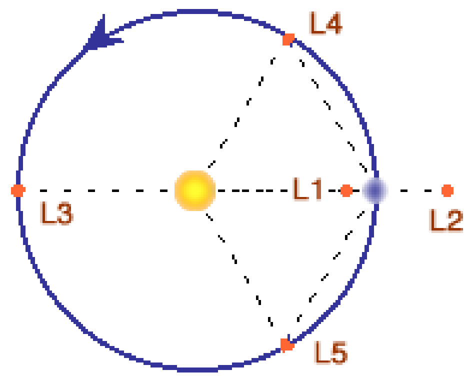
- The Mars day is about one Earth day plus 40 m. Its axis is inclined a bit more than Earth, so Mars has seasons.
- The Mars year is about two Earth years; the closest approach to Earth is every odd Earth year.
- It takes about a year to get to Mars, decelerate and circulaize the orbit, then a few weeks to entry, descent and land (EDL).
- NASA orbiters are in two-hour, Sun-synchronous, polar orbits, so the pass a lander twice a day, but only for about ten minutes each pass.
- During one pass commands are uploaded to the spacecraft; during the other telemetry and science data are downloaded to the orbiter and then from there to Earth.
- About 80 megabits can be downloaded on each pass at rates up to 256 kbps.



120
100
80
60
40
20
0
Data Volume Returned (Mbits)
0
10
20
30
40
50
60
70
80
90
Maximum Elevation During the Pass (deg)
Spirit
Opportunity
Poly. (Spirit)
Poly. (Opportunity)

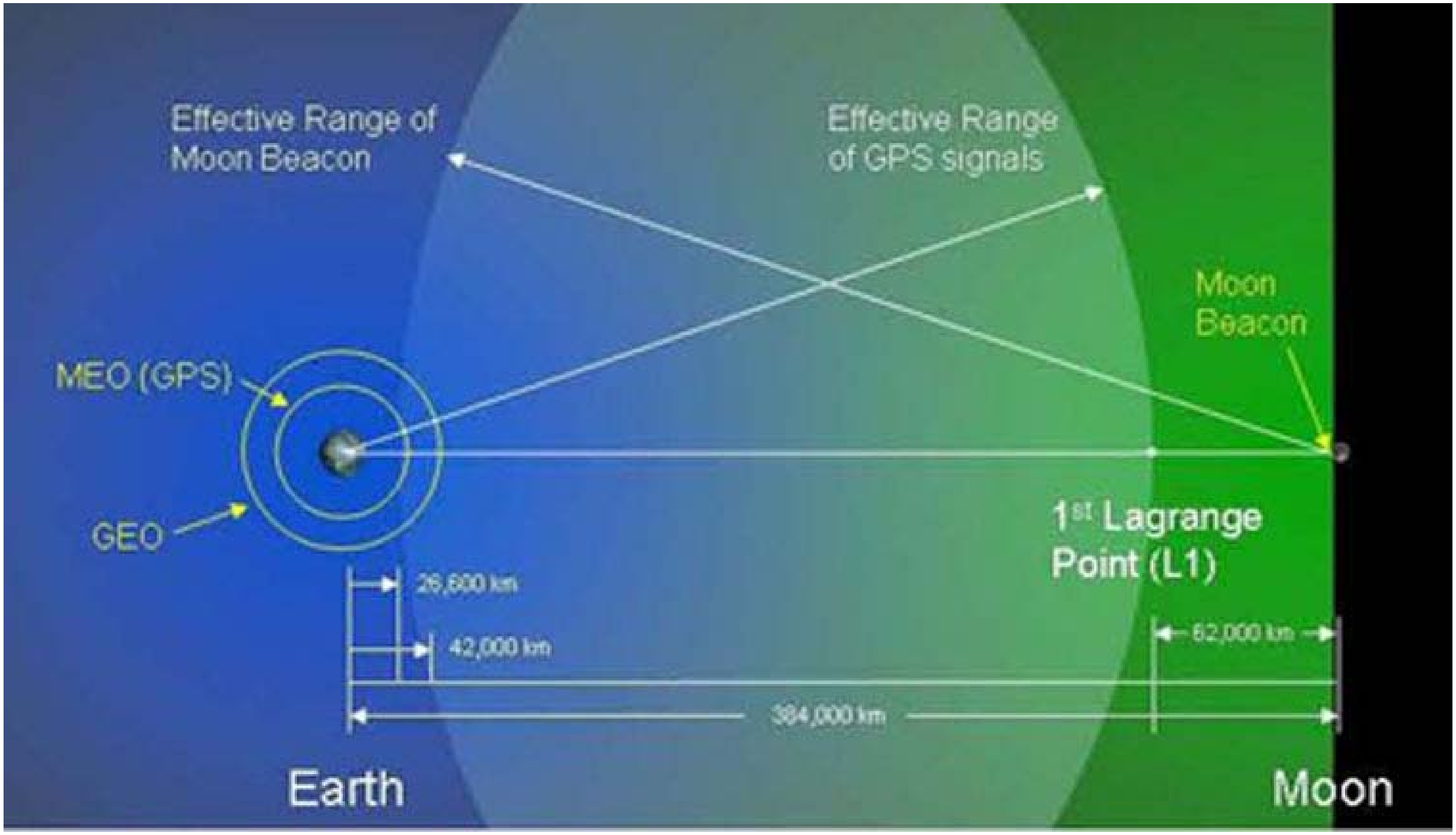
Planetary orbits and Lagrange points





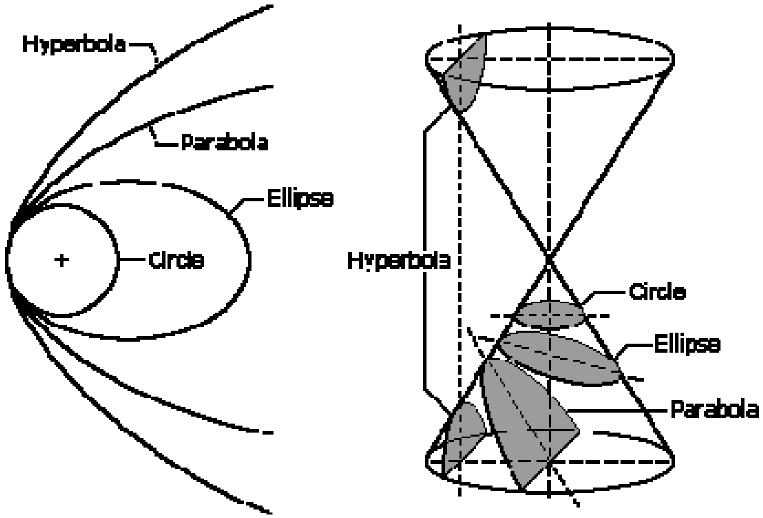
- Something is always in orbit about something else.
- The orbiter is almost always very tiny with respect to the orbited (primary) body.
- Add energy at periapsis to increase the apoapsis and vice versa.
- Add energy at apoapsis to increase the periapsis and vice versa.
- Lose energy to at apohelion for Mars orbit capture and aerobrake.

Time transfer to the Moon



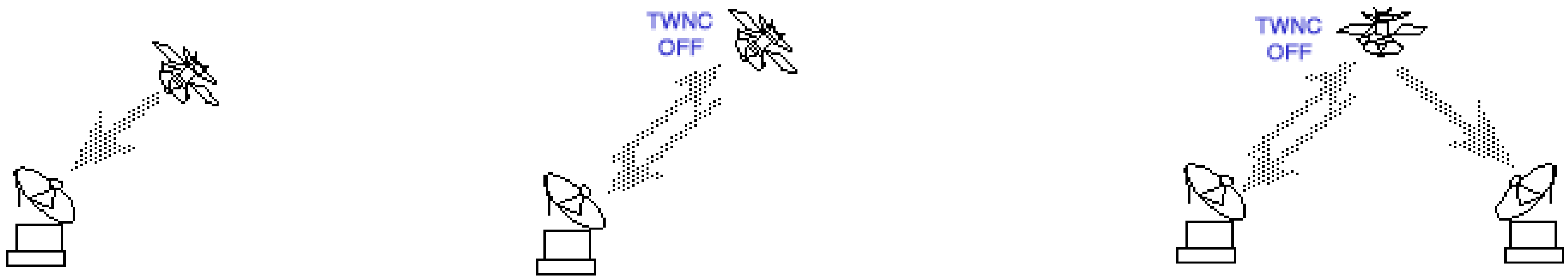
Keplerian elemente for Hubble Space Telescope

- Satellite: HUBBLE
  Catalog number: 20580
  Epoch time: 08254.95275816
  Element set: 0219
  Inclination: 028.4675 deg
  RA of node: 123.8301 deg
  Eccentricity: 0.0003885
  Arg of perigee: 212.6701 deg
  Mean anomaly: 147.3653 deg
  Mean motion: 15.00406242 rev/day
  Decay rate: 3.50e-06 rev/day^2
  Epoch rev: 80787 Checksum: 282



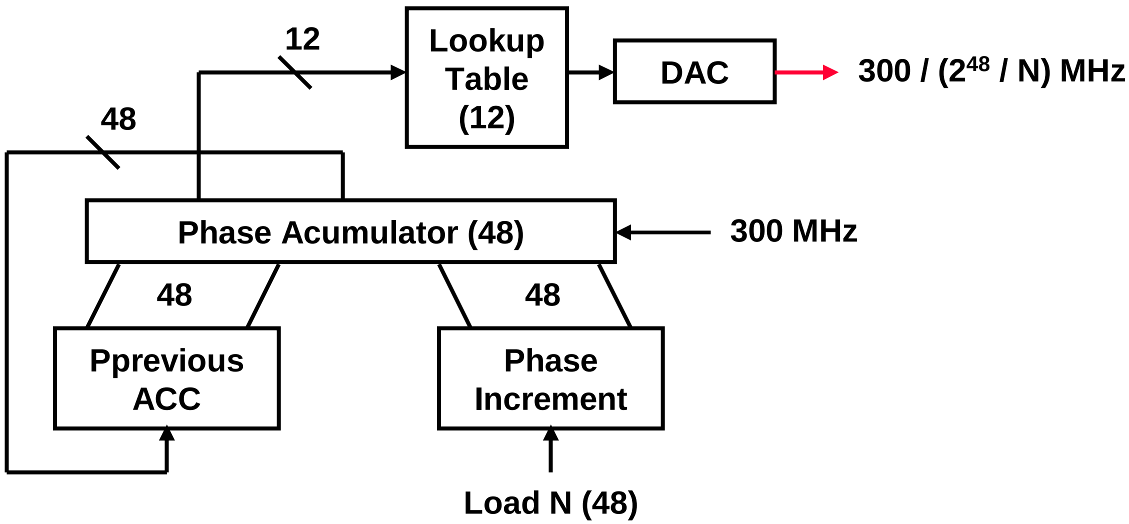
- **In practice the elements can be determined by the state vectors (range and range rate) at three different times along the orbit.**

Range and range rate measurements



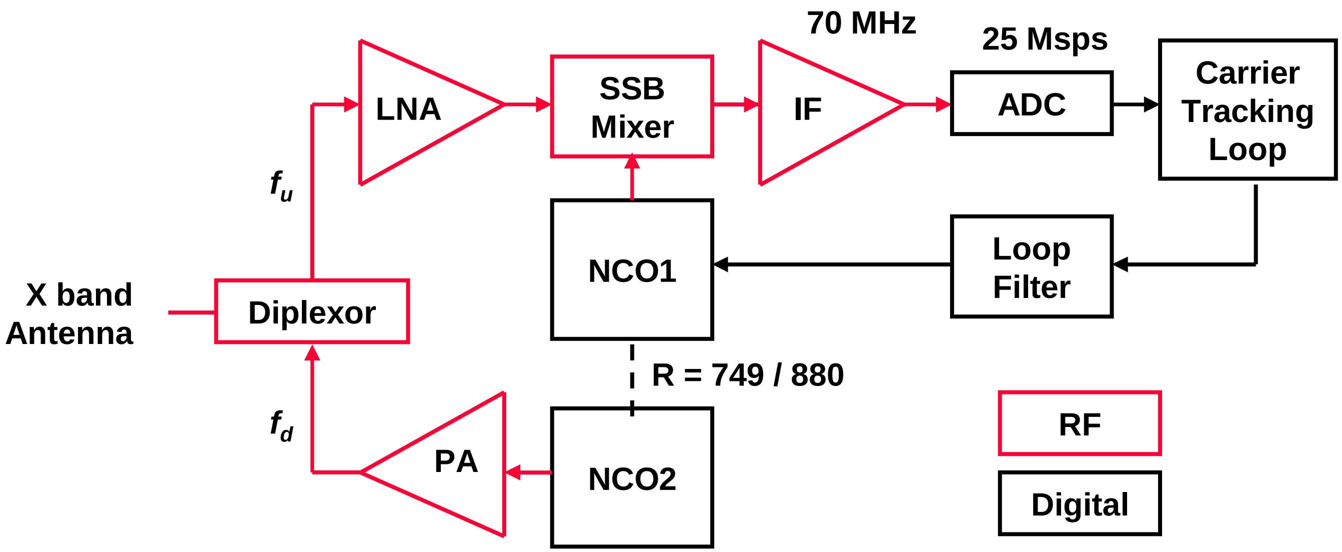
- Keplerian elements are determined from three range and range rate measurments.
- Range must be determined to 3 ns and range rate (doppler) to less than 1 Hz. This requires extraordinary oscillator stability at DSN stations.
- Good satellite oscillator stability is difficult and expensive .
- Tracking times can be long – up to 40 m.
- Solution is strict coherence between uplink and downlink signals.
- DSN station handover must be coherent as well.

Numeric-controlled oscillator (NCO)



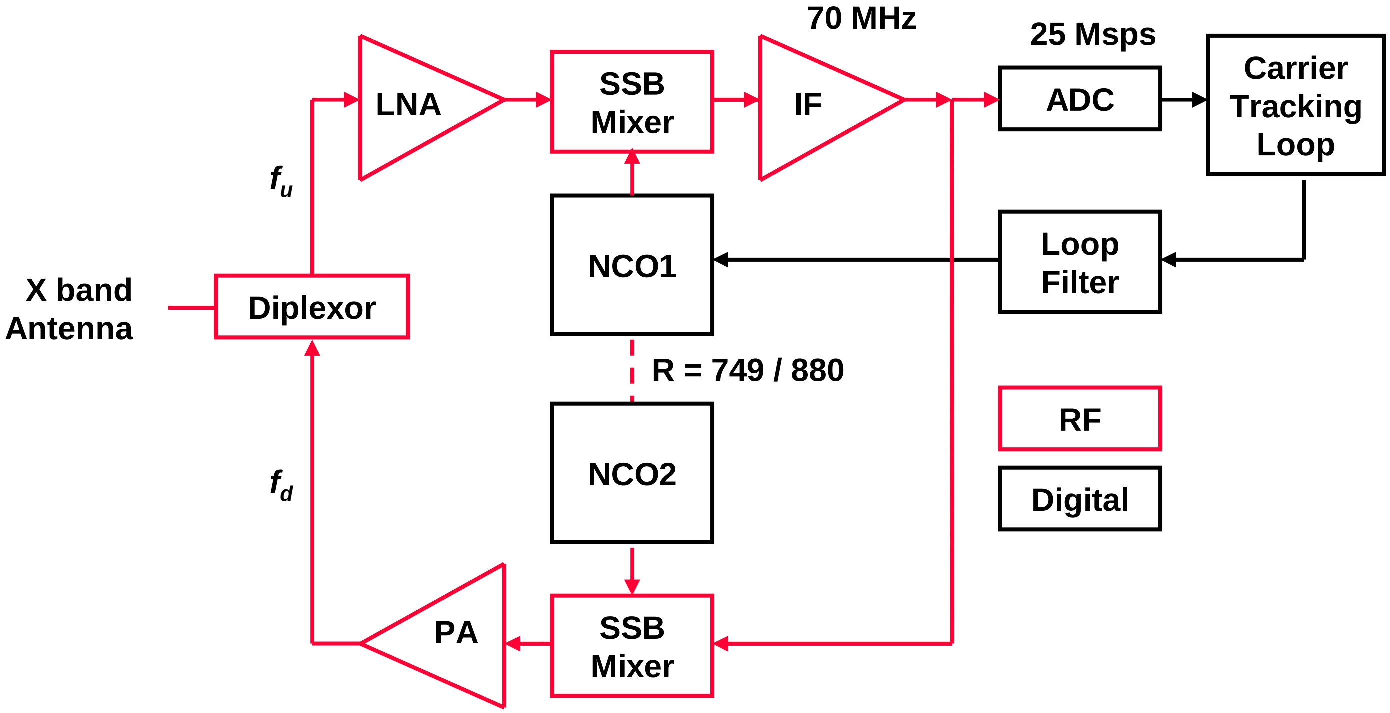
- This device can synthesize frequencoes in tha range 0-75 MHz with preicion of about 1 mHz. It works by dividing a 300-MHz clock by an integral value in the range $1\text{-}2^{46}$.
- The Analog Devices AD 9854 chip includes this NCO together with a BPSK/QPSK modulator, sweepe generator, 20x clock multiplier and amplitude control.
- The lookup table includes ¼ cycle of sine-wave samples. The high-order two bits map this table to all four analog quadrants.

Range rate turnaround



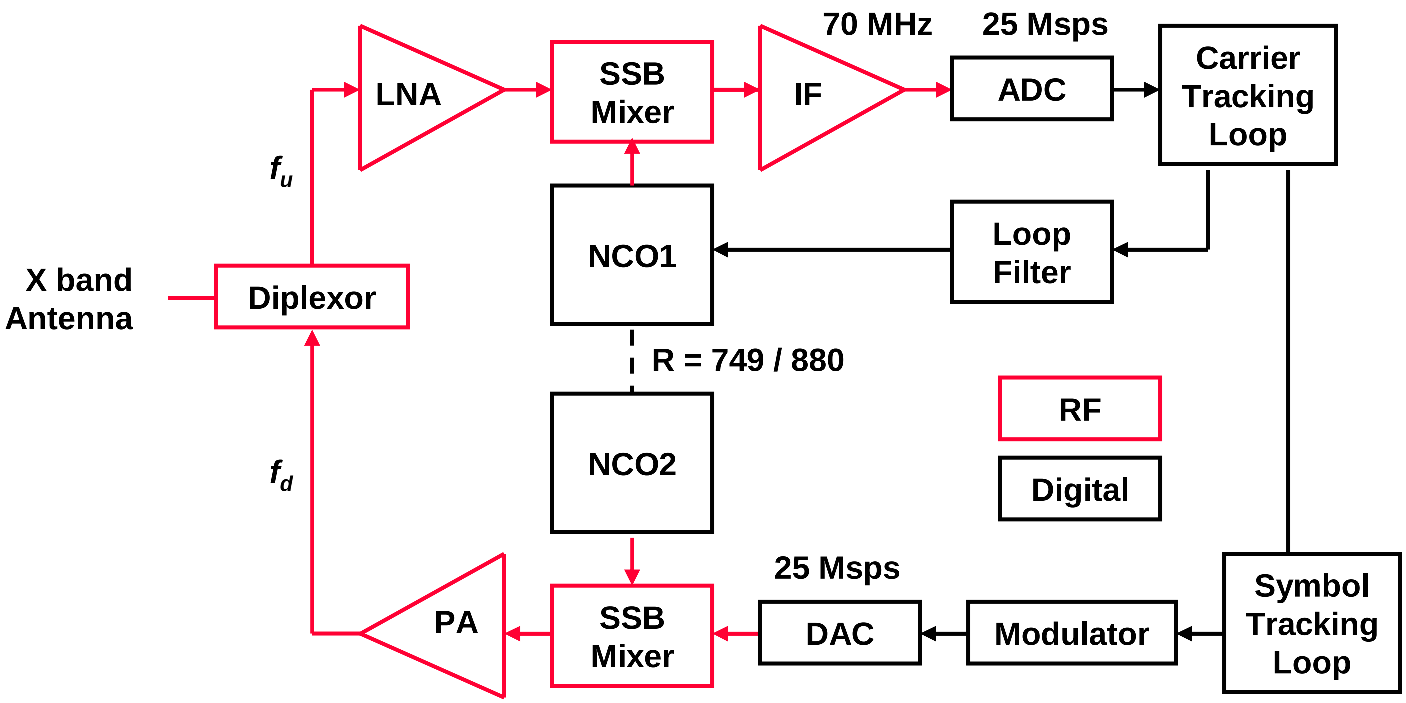
- The digital carrier tracking loop locks NCO1 on the received carrier at 70-MHz IF.
- The phase increment of NCO2 is calculated from the given ratio R at the 70-MHz IF.
- The DSN calculates the range rate $f_r = ½ (f_u – 1/R\ f_d)$

Non-regenerative range turnaround



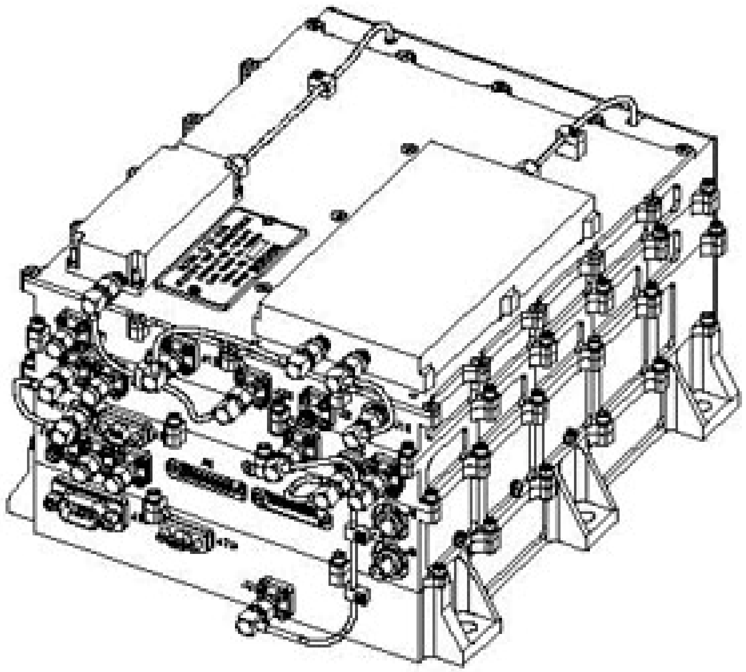
- This is often called a ***bent pipe***.
- **The digital carrier tracking loop locks NCO1 on the received carrier .**
- **The IF is filtered and upconverted by NCO2 to the downlink frequency.**
- **The DSN calculates the range from the PN signal.**

Regenerative range turnaround



- **Similar to bent pipe, except the PN signal is recovered, filtered and remodulated on the downlink.**
- **This improves the SNR at the DSN by about 17 dB.**

Electra transceiver



- There are three Electra radios
  - Original Electra for MRO (7 W)
  - Electra LITE for Phoenix (7 W; light weight)
  - Electra MICRO for balloons (100 mw)

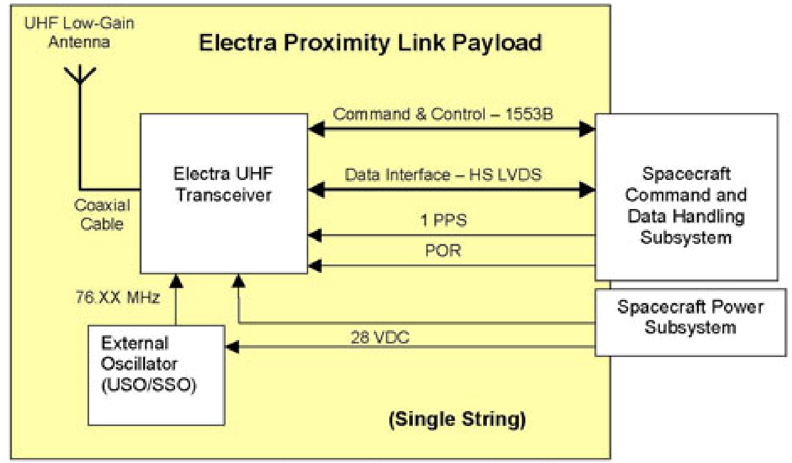


Figure 2: Electra Proximity Link Payload block diagram

Parameter	Electra UHF Transceiver
TX Frequency	FD: 435 to 450 MHz; HDO: 390 - 450 MHz
RX Frequency	FD: 390 to 405 MHz; HDO: 390 - 450 MHz
Duplex	Half & Full
Operational Modes	Sleep, Stdby, Rx, Tx, Rx/Tx
TX/RX Rate	1,2,4,8...2048 Ksps
Modulation	Manchester, NRZ-L, BPSK, QPSK Mod Index 60 & 90
Coding	Reed Solomon, K=7, R=1/2 Conv Encode/Decode
Spectrum Record	Open Loop Signal Sampling < 100 KSPS, 1-8 bits/sample
RX Noise Figure	FD: 4.9 dB; HDO:3.9 dB
RF TX Power	FD: 5.0 W; HDO: 7.0W
Protocols	Proximity-1
Reconfigurability	Yes
Doppler Obs	1-way/2-way
Mass	5005 gms (w/Diplexer)
Dimensions (l,w,h)	21.7 cm x 20.1 cm x 11.6 cm
DC Power -Sleep Mode	7.2W (WC, EOL)
DC Power - RX Mode	23.8 W (WC, EOL)
DC Power - TX/RX Mode	75.3 W (WC, EOL)
Parts Grade	B+
TID	20 Krad

Table 2: Key EUT Specifications

Design features

- This is a software defined digital radio that can be reconfigured via the data link. It operates at UHF frequencies (~400 MHz) at variable symbol rates to 4.096 MHz.
- It uses Reed Solomon, convolutional encoding and 3-bit soft Viterbi decoding.
- It can operate with either NRZ or Manchester encoding using either a Costas loop (NRZ) or PLL (Manchester) carrier tracking loop.
- It uses a concatenated integrate-comb (CIC) decimator, digital transition tracking loop (DTTL) for symbol synchronization.
- All this with no DSP chip and an absolutely humungus FPGA.
- An onboard computer implements a reliable link protocol with CRC and state machine.
- Including a $300 K ultra-stable oscillator, it ain't cheap.

Block diagram

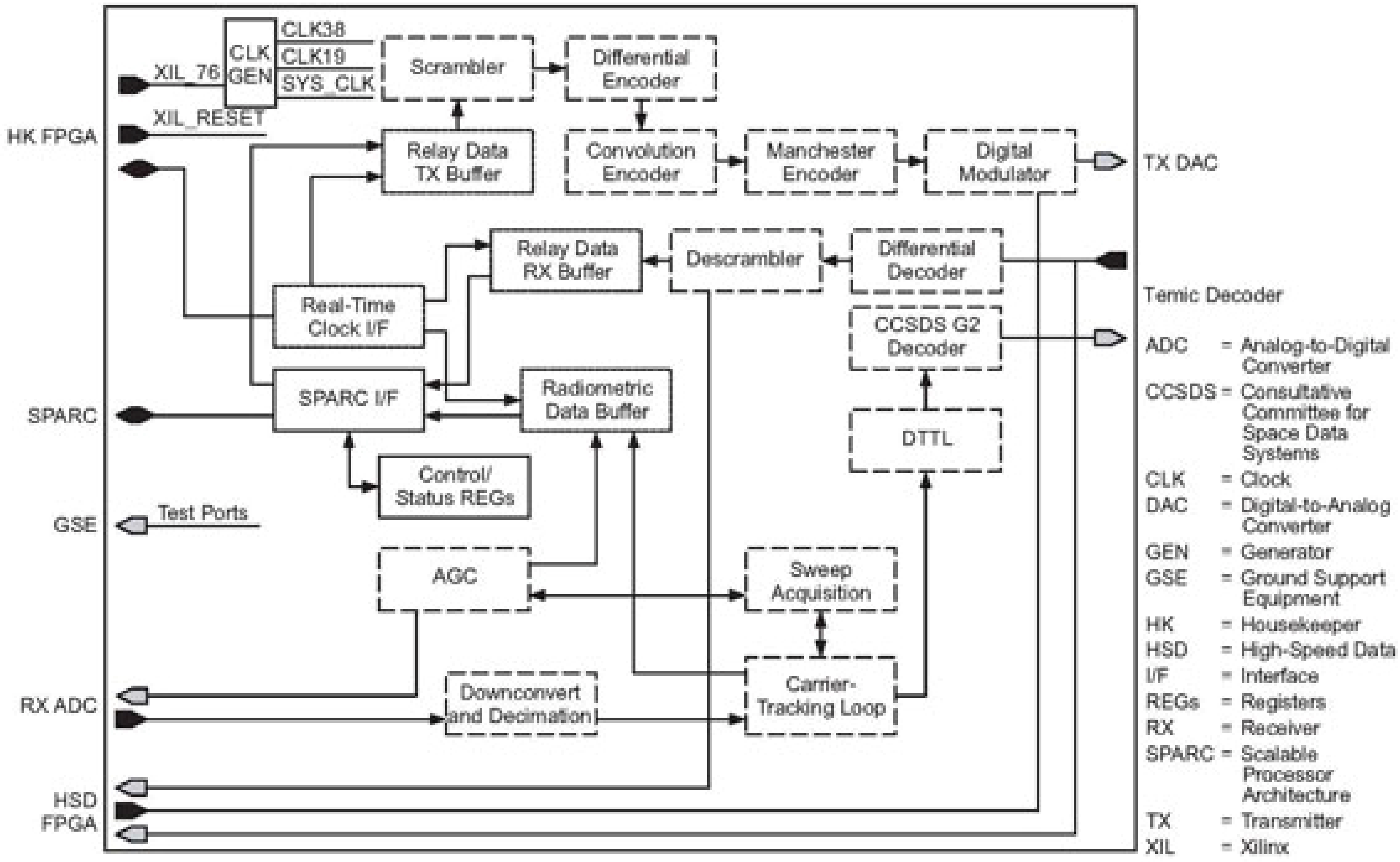


Fig. 2-1. Electra transceiver block diagram.

Concatenated integrate-comb decimator

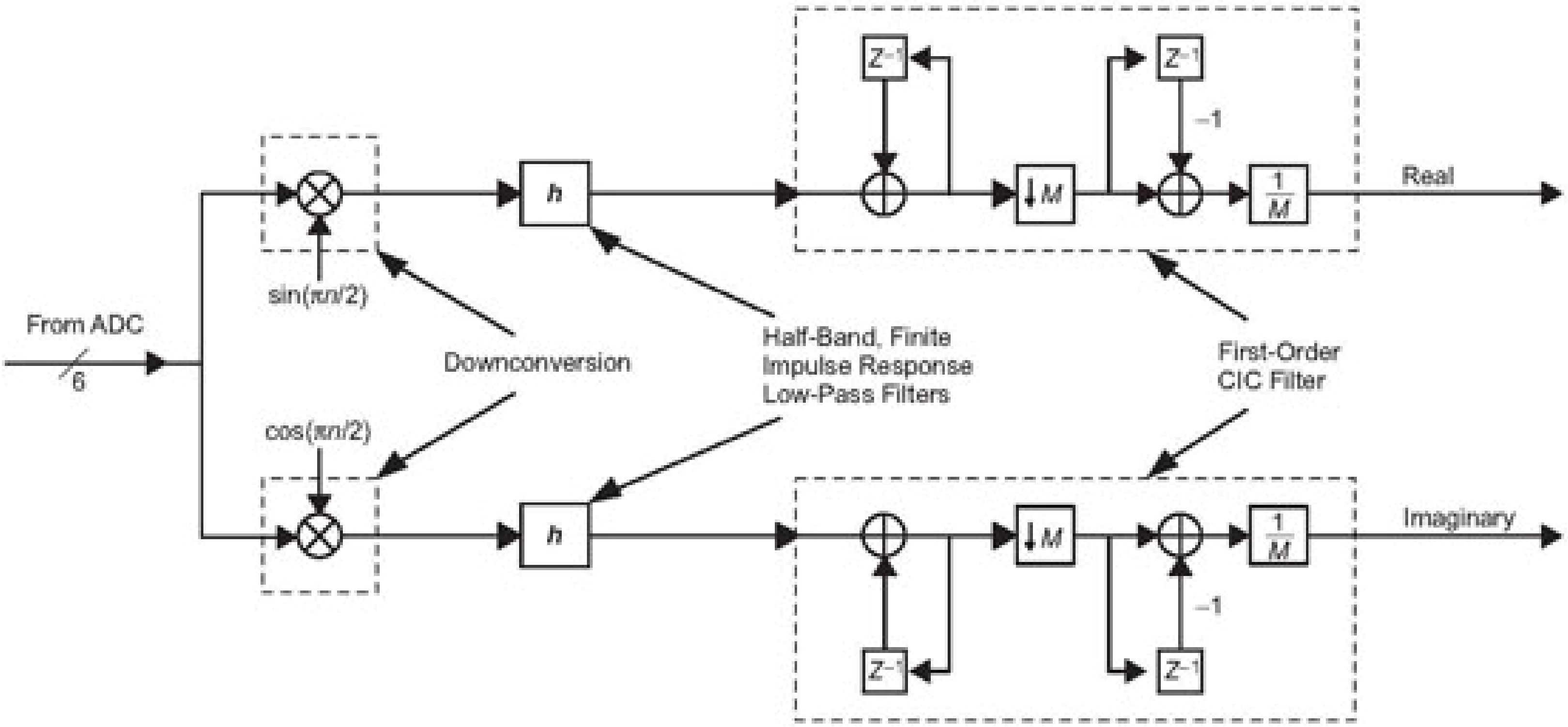
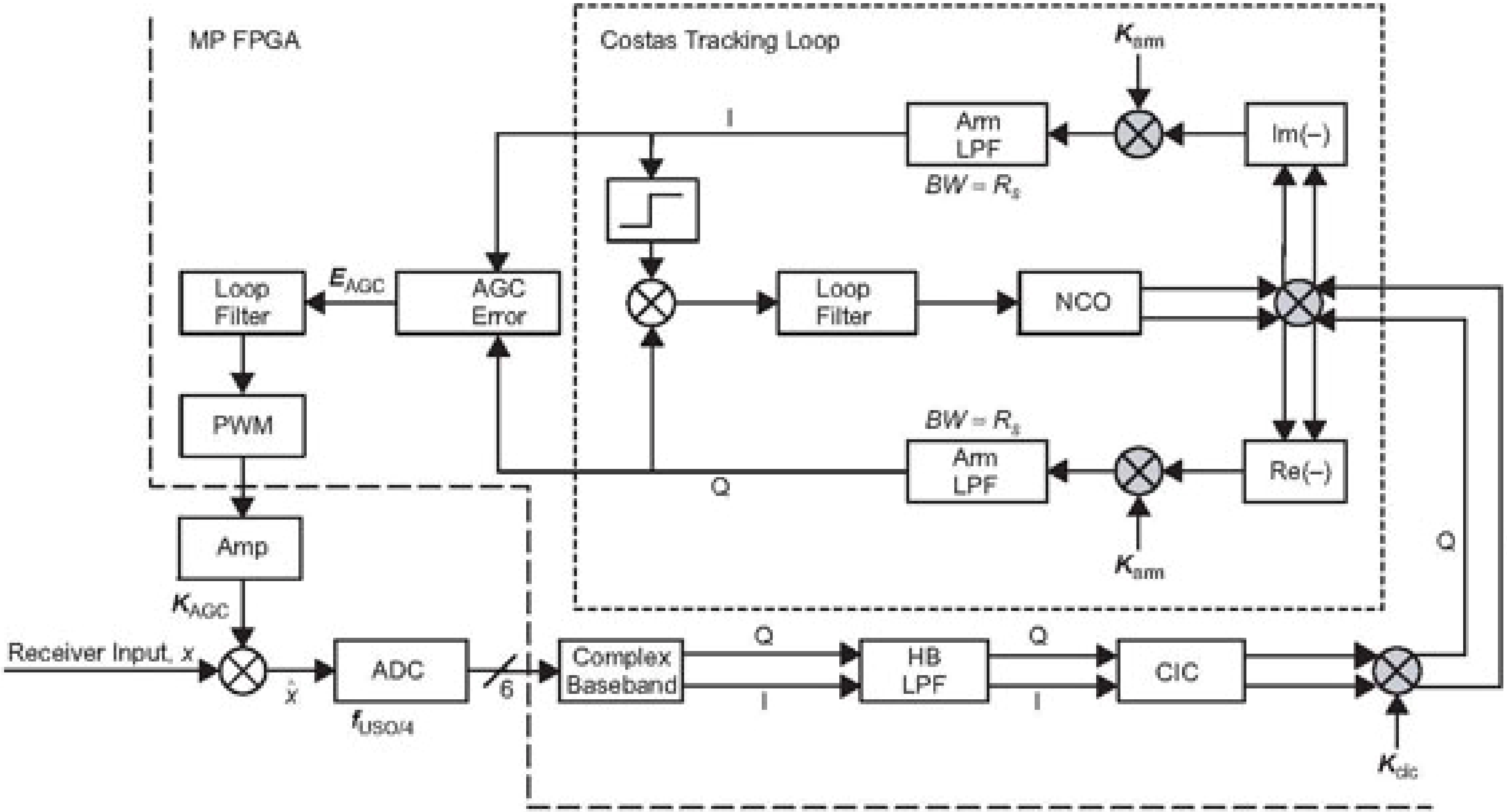


Fig. 2-3. Digital complex basebanding and decimation.

Costas carrier tracking loop



Amp = (Gain Control) Amplifier
HB = Half-Band
Im = Imaginary
LPF = Low-Pass Filter
MP = Modem Processor
PWM = Pulse-Width Modulator
Re = Real

Fig. 2-2. AGC control loop.

Block diagram of Costas/PLL carrier tracking loop

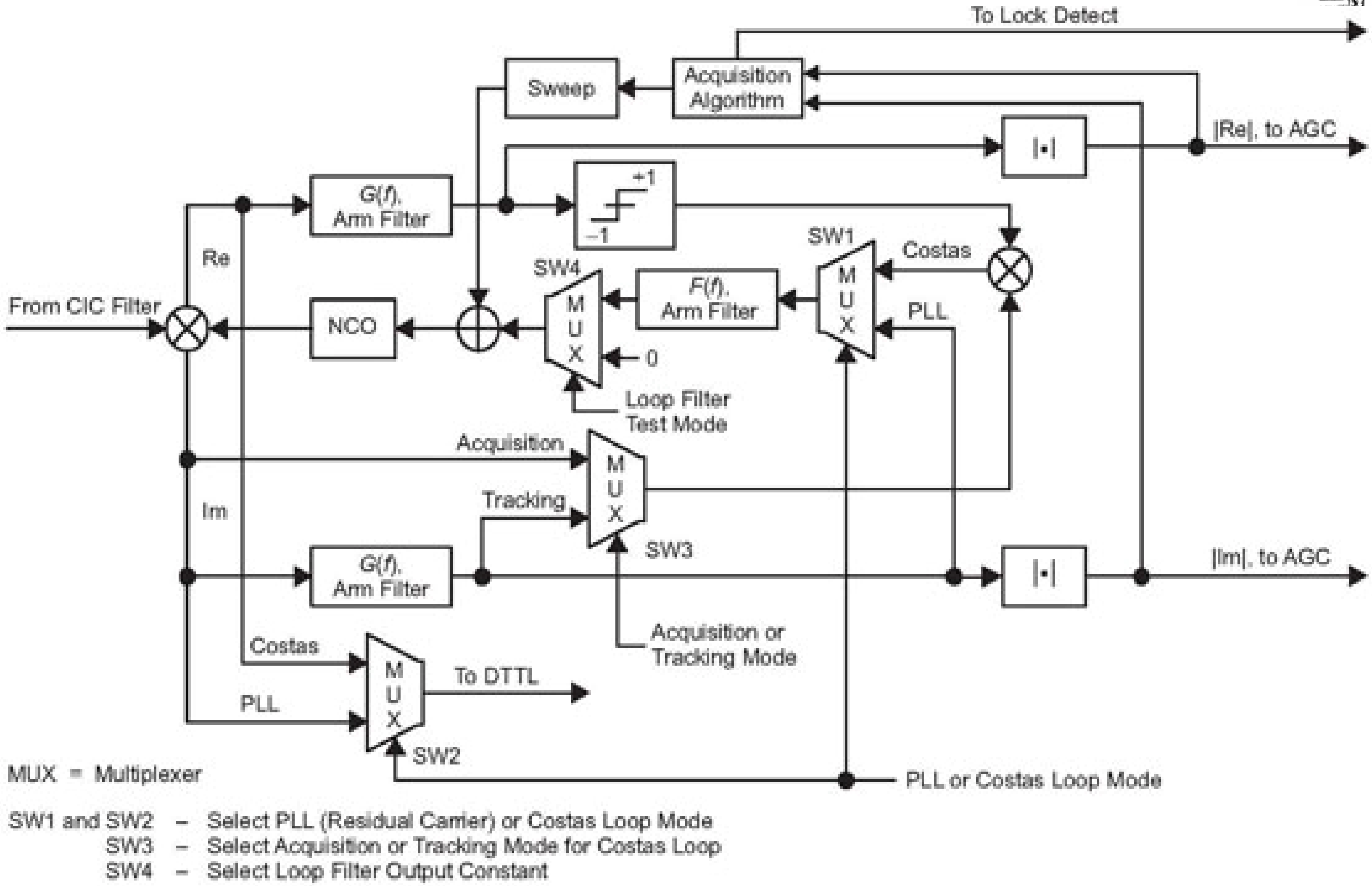
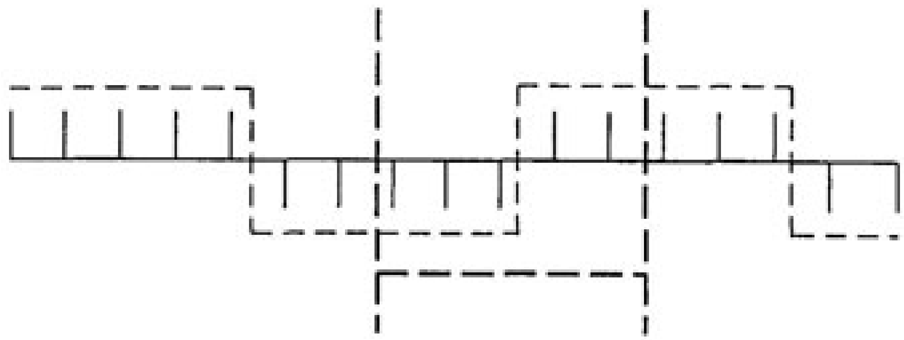


Fig. 2-4. Block diagram of the Electra carrier-tracking loop.

Digital transition tracking lop (DTTL)



(a) Three samples from the first symbol and two samples from second symbol

- The DTTL uses three integrators, where the symbol time is *T*
  - A 0-*T*/2 for the signal.
  - B *T*/2-*T* for the signal and and first half of the transition.
  - C *T*-3*T*/2 for the second half of the transition
- The symbol is A + B.
- The phase is B + C processed by a loop filter and NCO.

DTTL symbol synchronization

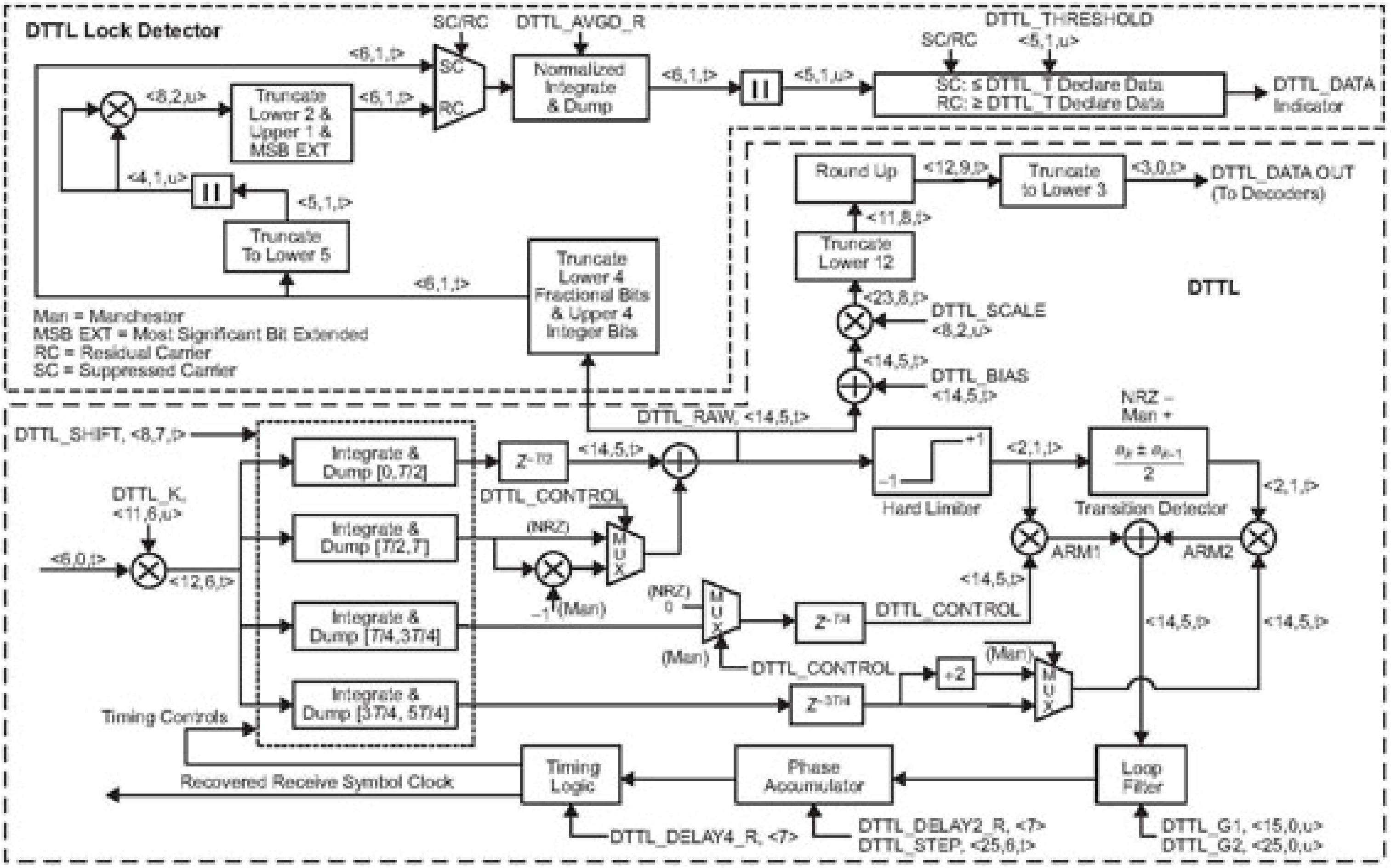


Fig. 2-5. Block diagram of the Electra symbol synchronization architecture.

Electra decimation vs. time resolution

Rate	Decimate	Samples	Res
4096	1	4	0.06
2048	1	8	0.06
1024	1	16	0.06
512	2	16	0.12
256	4	16	0.24
128	8	16	0.49
64	16	16	0.98
32	32	16	1.95
16	64	16	3.91
8	128	16	7.81
4	128	32	7.81
2	128	64	7.81
1	128	128	7.81

Digital modulator

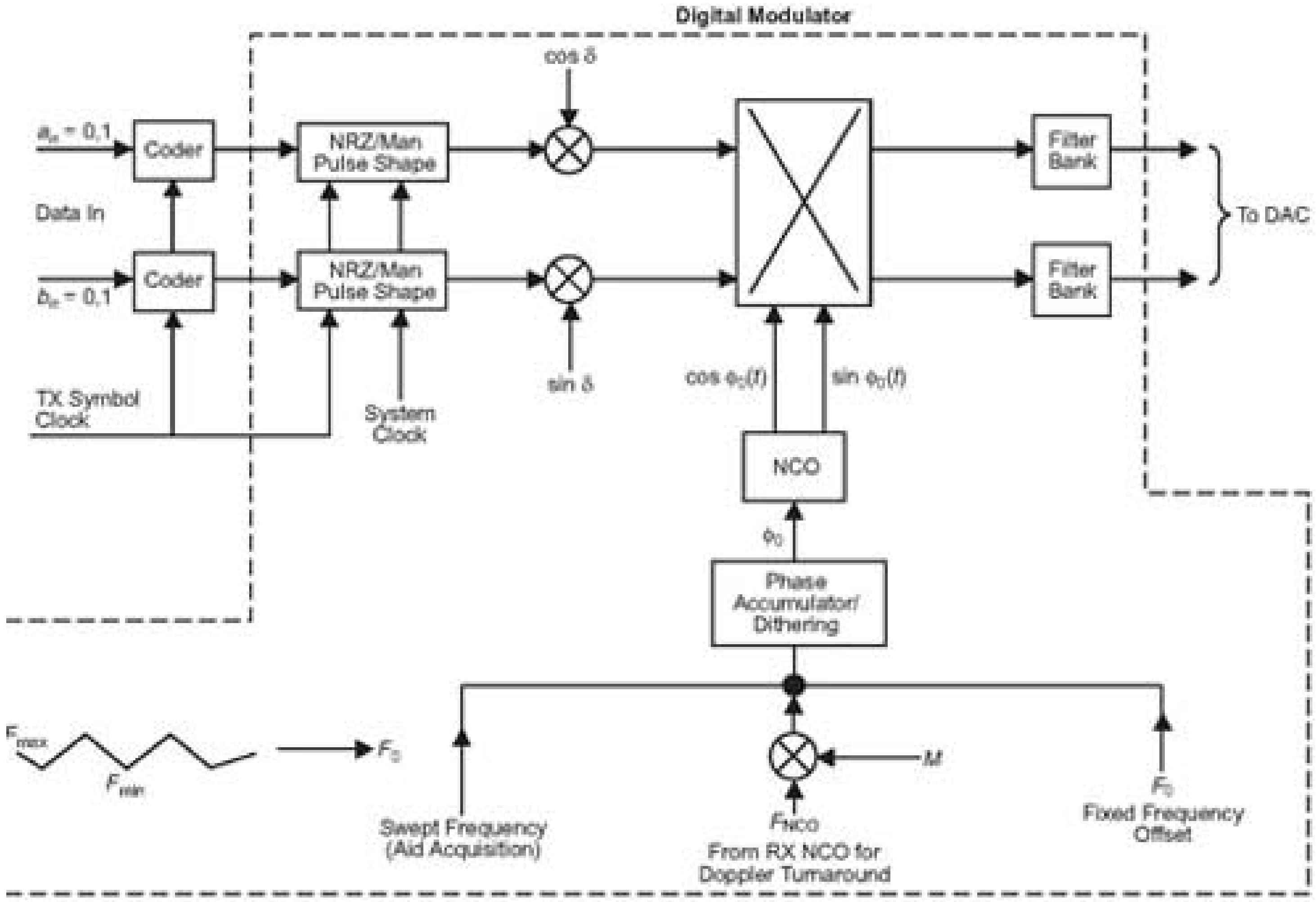


Fig. 2-9. Electra modulator block diagram.

Further information

- NTP home page http://www.ntp.org
  - Current NTP Version 3 and 4 software and documentation
  - FAQ and links to other sources and interesting places
- David L. Mills home page http://www.eecis.udel.edu/~mills
  - Papers, reports and memoranda in PostScript and PDF formats
  - Briefings in HTML, PostScript, PowerPoint and PDF formats
  - Collaboration resources hardware, software and documentation
  - Songs, photo galleries and after-dinner speech scripts
- Udel FTP server: ftp://ftp.udel.edu/pub/ntp
  - Current NTP Version software, documentation and support
  - Collaboration resources and junkbox
- Related projects http://www.eecis.udel.edu/~mills/status.htm
  - Current research project descriptions and briefings