Timekeeping in the Interplanetary Internet

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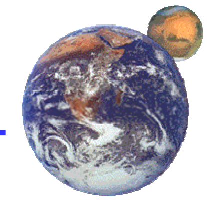
Interplanetary Internet (IPIN)



- Research program funded by DARPA and NASA
- Near term emphasis on Mars exploration and mission support
- Exploration vehicles
  - Surface base stations and rovers – perform experiments, collect data
  - Satellite orbiters – relay commands to surface vehicles, retrieve data for later transmission to Earth
  - Spacecraft – transport orbiters and surface vehicles to Mars
- Mission support
  - NASA Deep Space Network (DSN) – three huge antennas in California, Spain and Australia, time shared for Mars and other NASA missions
  - Earth internet – coordinate mission activities, send commands and retrieve data via DSN, disseminate results
  - MARS internet – communicate between DSN, orbiters and surface vehicles; perform housekeeping functions such as antenna pointing, network routing, ephemeris maintenance and general timekeeping

IPIN issues

- Transmission delays between Earth and Mars are variable and in general much longer than in Earth and Mars internets
- Transmission speeds are highly variable, but in general far slower than Earth internet
- Spacecraft position and velocity can be predicted accurately, so transmission delays can be predicted
- Connectivity between Mars surface and orbiters and between Earth and Mars is not continuous, but opportunities can be predicted
- DSN facilities are shared; connectivity opportunities must be scheduled in advance for each mission
- Error recovery using retransmissions is impractical; TCP is useful only in Earth internet and Mars internet, but not between Earth and Mars
- Dependency on Earth-based databases is not practical on Mars, so any databases required must be on or near Mars

IPIN architecture

- IPIN service between Earth and Mars internets is not real time
  - Similar to electronic mail, but with important differences
  - Data can be queued by the network for later delivery
  - Data can be retrieved by the network when a transmission opportunity occurs
- Earth and Mars internets are separate and distinct
  - Each uses conventional TCP/IP architecture and packet switching principles
  - Internet address spaces are separate and distinct
  - Name-address resolution functions are separate and self contained
- DSN segment isolated by gateways on Earth and in Mars orbit
  - Gateways take custodial responsibility for commands and data prior to scheduled or predicted transmission opportunities
  - DSN transmissions include one or more “bundles” consisting of commands and data addressed to an Earth or Mars gateway
  - Onward transmission beyond the gateway requires domain name resolution using a database in the destination internet

IPIN timekeeping models

- Earth segment
  - Synchronizes stationary NTP time servers and clients to UTC
  - NTP messages exchanged at relatively frequent intervals
- Mars segment
  - Synchronizes orbiters and surface vehicles to planet Mars clock
  - Must account for the vehicle position and velocity relative to planet Mars reference
  - Messages exchanged at opportunistic intervals using piggybacked commands and data
- DSN segment
  - Synchronizes the planet Mars clock to UTC
  - Must account relative position and velocity between DSN stations and Mars vehicles

Timescales

- International Atomic Time (TAI)
  - Determined by a ensemble of cesium oscillators at national standard laboratories
  - SI standard second 9,192,631,770 oscillations of the cesium atom
  - Origin defined ET + 32.184 s at 0^h 1 January 1977
- Astronomical time (UT1)
  - Measured as the hour angle between the zenith meridian at Greenwich and the “mean” sun
  - Drifts slowly with periodic variations from TAI
  - Used prior to atomic time for civil timekeeping
- Universal Coordinated Time (UTC)
  - Runs at the same rate as TAI
  - Origin is 0^h 1 January 1972, 10 s behind TAI
  - Occasional insertions of a leapsecond in order to maintain agreement with UT1, some 32 s behind TAI in 2001

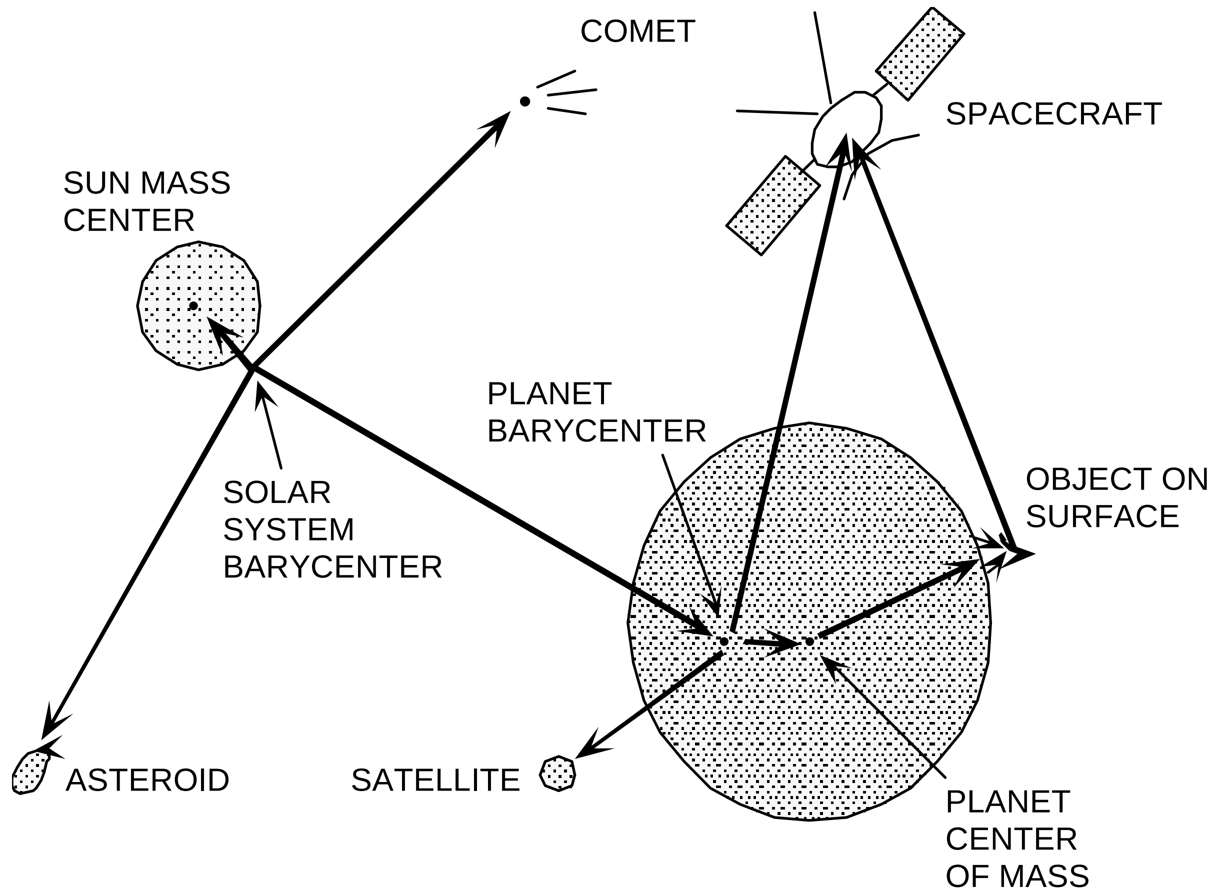
Astronomical timescales

- Ephemeris Time
  - Based on Earth motion around the Sun
  - Epoch is the number of solar days and fraction since 12h 1 January 1900
  - Ephemeris second is 1 / 31,556,925.9747 of the tropical year that began at the epoch 0 January 1900 at 12h ET.
  - Defined TAI + 32.184 s at 0^h 1 January 1984
- Greenwich Mean Siderial Time (GMST)
  - Hour angle of the vernal equinox
  - Siderial second is 365.25 / 366.25 of UT1 second, since the Earth makes one additional rotation each year - 23h 56m 4.0905s
  - Mean Solar Time UT0 = UT
  - Moves with constant velocity along celestial equator
  - Difference between Siderial Time and Mean Solar Time is equation of time

Heavenly oscillators

- Terrestrial Dynamical Time (TDT or TT)
  - Proper time on Earth at sea level
  - Runs at TAI rate
  - Reference epoch TAI + 32.184 s at 12^h 1 Jan 2000
- Barycentric Dynamical Time (TDB)
  - Ideal time at the solar system barycenter (center of mass)
  - Reference epoch same as TDT
  - Intervals measured between two epoches measured in TDT may not be the same in TDB, but variations are small - about 1.6 ms – due to relativistic effects
  - TDB = TT + .001658 sin(g) + .000014 sin(2g) s, where
  - G = 357.53 + 0.9856003 (JD – 2451545.0) and
  - JD = Julian Day, assumed here measured in UT

IPIN time references



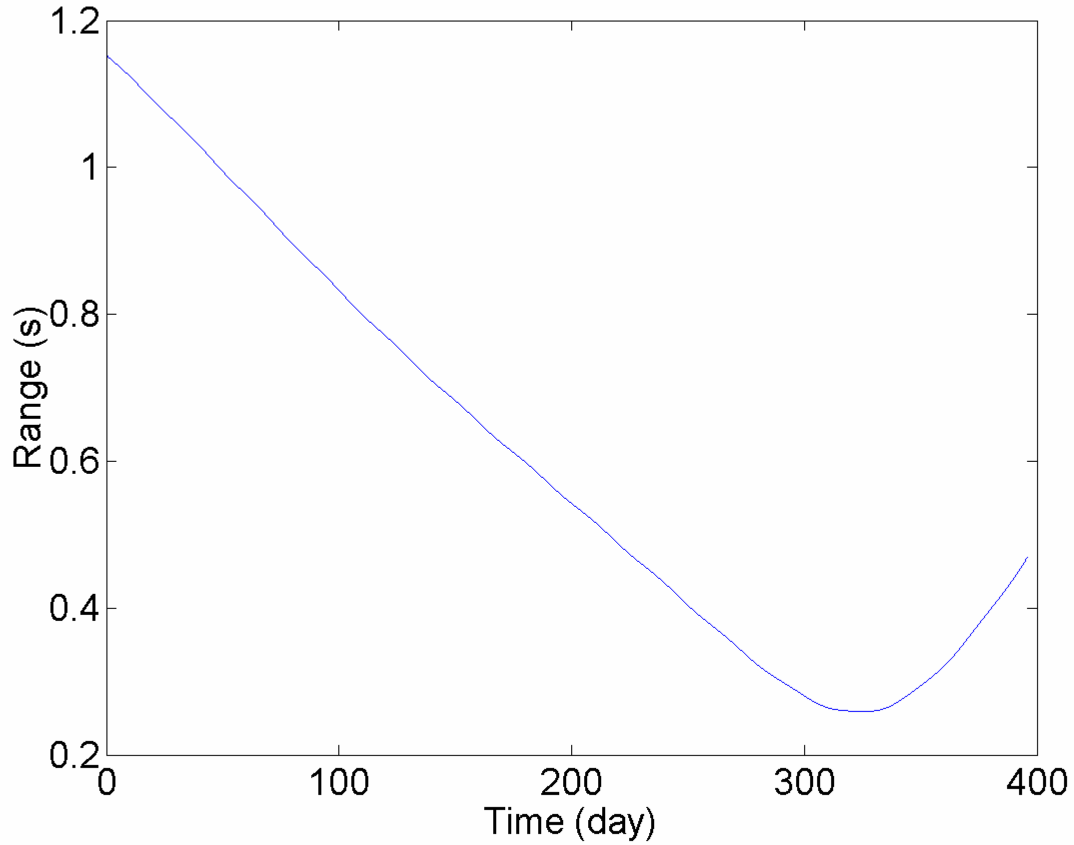
Interplanetary NTP

- All clients and servers operate on UTC timescale for compatibility with current Earth Internet.
- Servers and clients have onboard ephemeris and SPICE routines to calculate position at any given UTC time.
- Servers broadcast NTP packets at intervals to be determined.
  - Servers send a transmit timestamp and compute ephemeris position according to server clock.
  - Clients record an apparent receive timestamp and compute ephemeris position according to client clock.
  - A client calculates the actual receive timestamp as the free-space propagation time between transmit and receive positions plus the transmit timestamp..
  - The client corrects the clock and computes a new position based on the corrected clock, then calculates a new propagation time and actual receive timestamp.
  - The client iterates this procedure until the corrections converge.

Present status

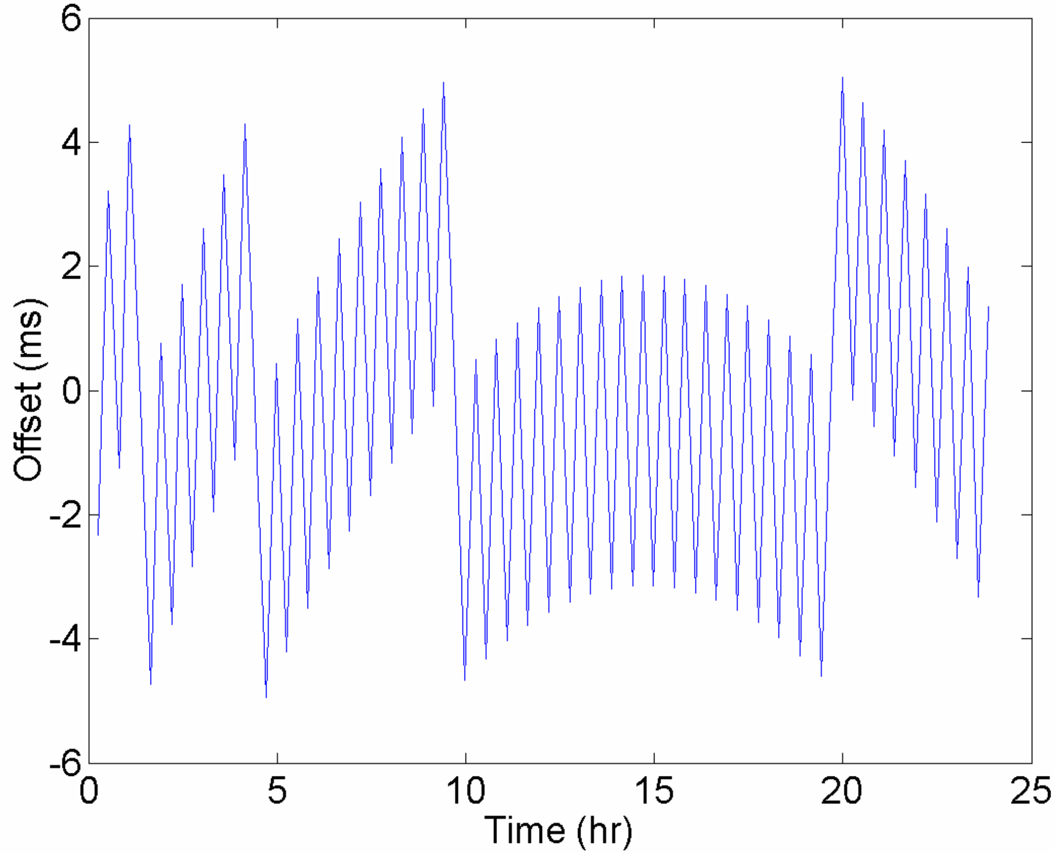
- The NTP daemon has been enhanced with a simulation capability.
  - The program is embedded in a discrete event simulator and uses the same code for both simulation and actual operation.
  - We have completed a proof of concept experiment involving an Earth-Mars path and the routines and example ephemerides in the SPICE toolkit.
  - The results were a little surprising and revealed that the “jitter” due to ephemeris determination and interpolation was somewhat greater than the NTP algorithms were prepared for.
  - Obviously, the NTP clock discipline loop parameters need to be re-optimized.

Earth-Mars lighttime range



- Earth-Mars lighttime range (s) over some 400 days calculated from ephemerides.
- This is used to compensate for the delay before handing off to the NTP algorithms.

NTP jitter



- Residual jitter measured by NTP after lighttime compensation
- This may be due to Chebyshev interpolation residuals.

Future plans

- Determine the Allan intercept characteristic for typical space channels.
  - Ephemeris jitter can be much worse than Internet jitter, even in the old days with the circuit to Norway.
  - Oscillator wander can be much worse then typical computer oscillators due to wider temperature variations.
- Estimate clock discipline parameters based on the Allan intercept.
  - The various step thresholds and popcorn spike parameters will probably change as well.
- Design and execute a test program to confirm nominal operation.
  - The program should involve a selection of paths in Earth-spacecraft and near-Mars configurations.
  - Determine whether NTP symmetric modes could improve accuracy.
- Wild card: dust off Highball technology for route and transmission scheduling.

NTP online resources

- Network Time Protocol (NTP) Version 3 Specification RFC-1305
  - NTPv4 features documented in release notes and reports cited there
- Simple NTP (SNTP) Version 3 specification RFC-2030
  - Applicable to IPv4, IPv6 and ISO CNLS
- List of public NTP time servers (as of May 2001)
  - 107 active primary (stratum 1) servers
  - 136 active stratum 2 servers
- NTP Version 4 implementation and documentation for Unix, VMS and Windows
  - Ported to over two dozen architectures and operating systems
  - Utility programs for remote monitoring, control and performance evaluation
  - Complete documentation in HTML format
- Collaboration resources at http://www.eecis.udel.edu/~mills/resource.htm

Further information

- Network Time Protocol (NTP): 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: 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
- FTP server ftp.udel.edu (`pub/ntp` directory)
  - Current NTP Version 3 and 4 software and documentation repository
  - Collaboration resources repository
- Related project descriptions and briefings
  - See "Current Research Project Descriptions and Briefings" at http://www.eecis.udel.edu/~mills/status.htm