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 an 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\textsuperscript{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\textsuperscript{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 0h 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\textsuperscript{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

SUN MASS CENTER

COMET

SPACECRAFT

ASTEROID

SOLAR SYSTEM BARYCENTER

PLANET BARYCENTER

OBJECT ON SURFACE

PLANET CENTER OF MASS

SATELLITE
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.

2-Aug-04
Residual jitter measured by NTP after lighttime compensation

This may be due to Chebyshev interpolation residuals.

2-Aug-04
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 than 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

  - 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