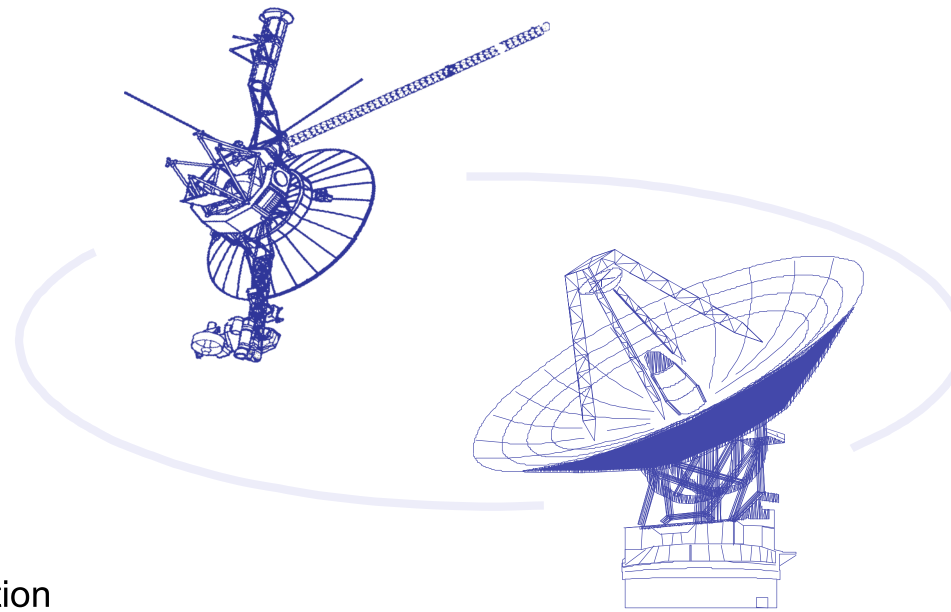
Applications of Clocks to Space Navigation & “Planetary GPS”

April 20, 2004



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*This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration

Outline of Presentation

- How GPS "works" for tracking and navigation at Earth
- Importance of clocks for GPS
- Deep Space Tracking
- Concepts for communications/navigation systems at other planetary bodies
- Sparse GPS-like planetary systems and tracking/navigation

How GPS Works

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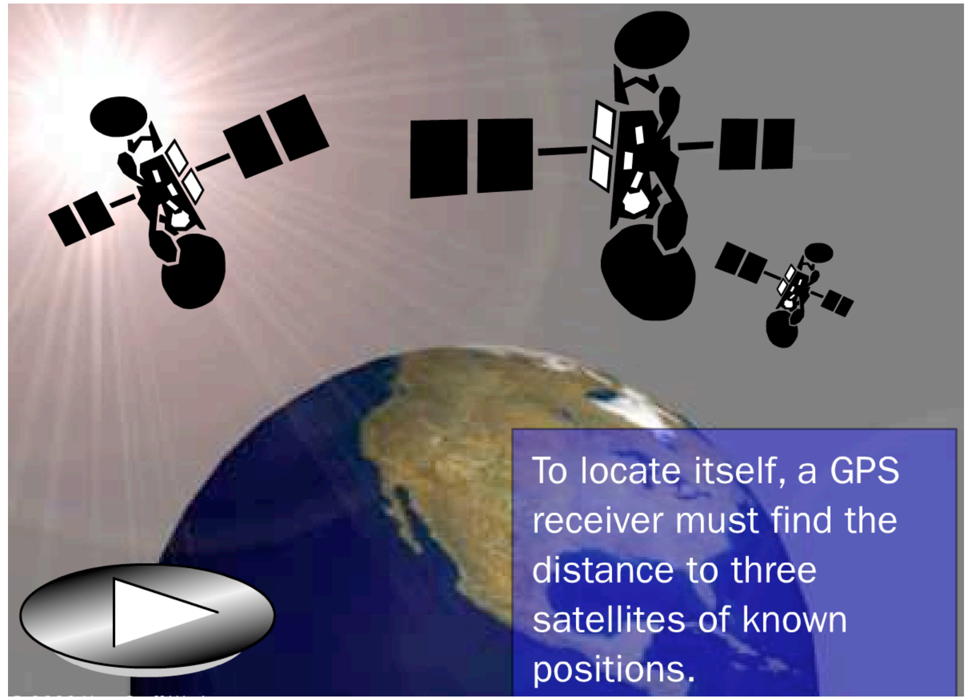
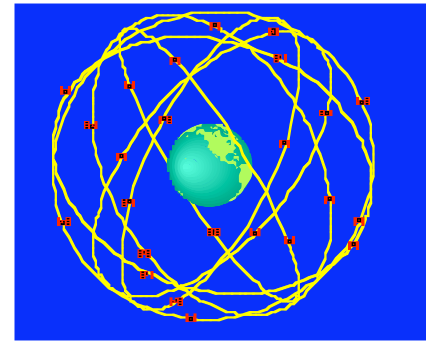
- GPS determines user position via “triangulation” to three GPS satellites
- The user’s GPS receiver compares each satellite’s unique pseudorandom code to models stored in the receiver to measure the time delay, and hence distance, to each GPS satellite
  - Requires that all GPS satellites be “synchronized” to “same” time
  - User does not need a good clock: a fourth GPS measurement determines the user time offset from “GPS time”
- Each GPS satellite continuously broadcasts its ephemeris and offset from “GPS time,” which is defined precisely relative to highly stable ground clocks. With these data, a GPS user receiver can in real-time uniquely determine its location (and time offset from “GPS time”) by tracking four GPS satellites



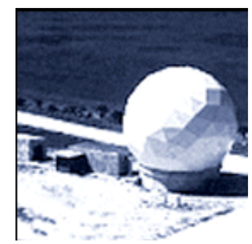
Each GPS satellite transmits a unique pseudorandom code

How GPS Works (cont.)

- **Operational Control Segment (OCS).** The USAF OCS consists of one Master Control Station (MCS) at Schriever AFB in Colorado Springs, plus monitor stations at the MCS, Hawaii, Kwajalein, Diego Garcia and Ascension Island. The stations passively track ranging data from all GPS in view. The MCS estimates and predicts each **satellite's ephemeris** and **clock** parameters and periodically uploads them to each GPS for re-transmission in its navigation message.



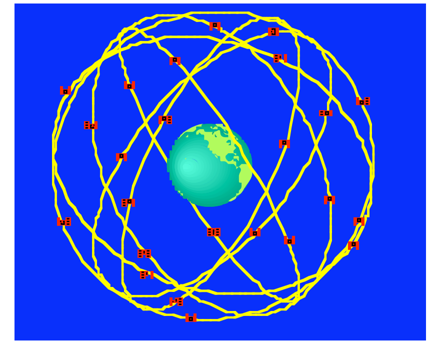
- GPS ephemeris/clock uploads are updated every several hours. During that time period, the broadcast ephemeris degrades only moderately because …
  - GPS are in relatively high-altitude, well-behaved orbits
  - GPS all carry precise (atomic) clocks
  - Knowledge of GPS time is maintained through the very stable ground clocks at the ground tracking sites

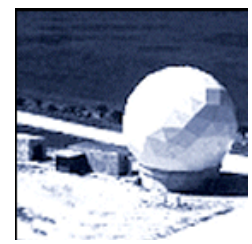


GPS MCS

How GPS Works (cont.)

- **The Design Trade for GPS.** The GPS designers incorporated …
  - Accurate (atomic) clocks at operational ground tracking sites and onboard the GPS satellites
  - A 24/7 global tracking network to accurately and continuously determine and update GPS orbits and clocks
  - *In contrast: the GPS user typically carries relatively simple equipment and does not require a good clock*
- The U.S. government elected to invest in robust and reliable GPS space and ground/control segments (infrastructure), thus enabling the user segment (millions of users) to carry relatively simple and cheap user equipment
- Roughly $12B to develop GPS (in 1980s)



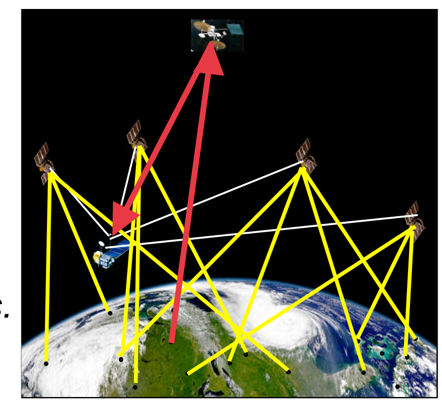


GPS MCS

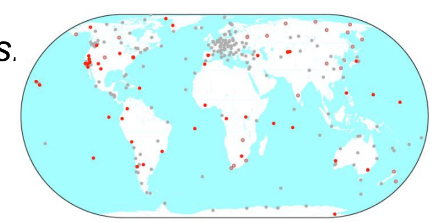
GPS Performance Today

- Standalone commercial receiver (handheld, autos, boats etc.)
  - **10 meters** real-time positioning.
    - *Performance is limited by GPS clock & orbit modeling.*

- Commercial receiver with differential services
  - **2 meters** real-time positioning. Requires local/regional differential service subscription.
    - *Performance is limited by GPS clock & orbit modeling.*



- JPL precision global differential GPS (GDGPS) system
  - **10 cm** real-time positioning accuracy. Requires global differential service from commercial partner.
    - *Network processing improves orbits and eliminates dependence on clocks.*
- Non-real-time (minutes to days) geodetic positioning
  - Better than **1-cm** non-real-time positioning accuracy. Requires global network data + special software.
    - *Network processing improves orbits and eliminates dependence on clocks.*



Applications of Clocks to Space Navigation & "Planetary GPS"

Spacecraft Navigation with JPL Blackjack GPS Receivers

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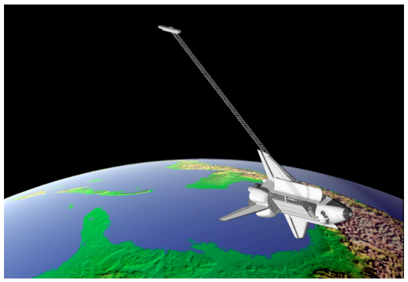
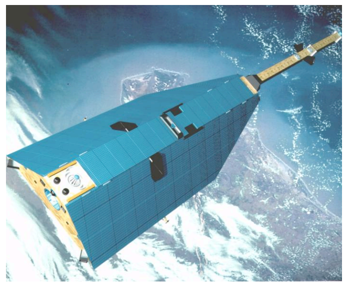
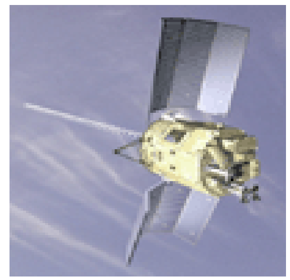
Of all these, only the GRACE GPS receivers carried high-quality clocks (USOs).



45-cm accuracy
SRTM
Feb 2000

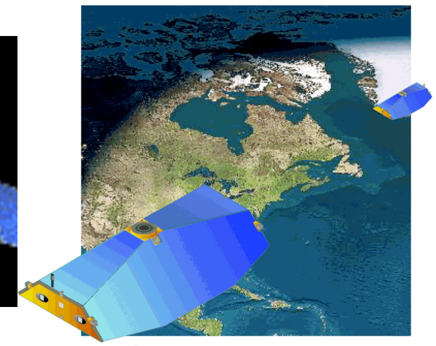


4-cm accuracy
CHAMP
Jul 2000



4-cm accuracy
Sub-meter real-time demo
SAC-C
Nov 2000

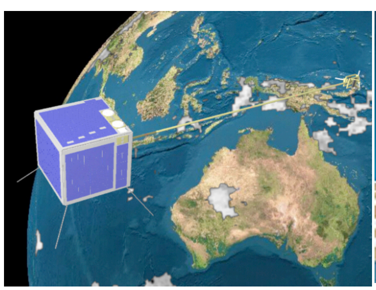
1-cm accuracy
JASON-1
Dec 2001



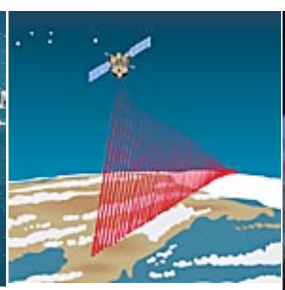
1-cm accuracy
GRACE
Mar 2002

Missions In Development

Dec 2002
FedSat



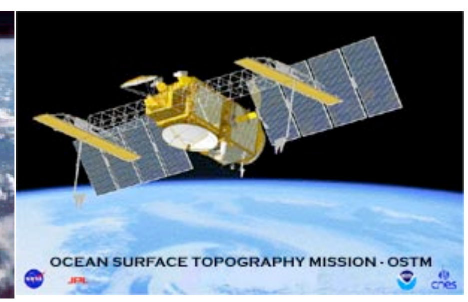
Dec 2002
ICESat



5-cm accuracy

Sept 2005
COSMIC

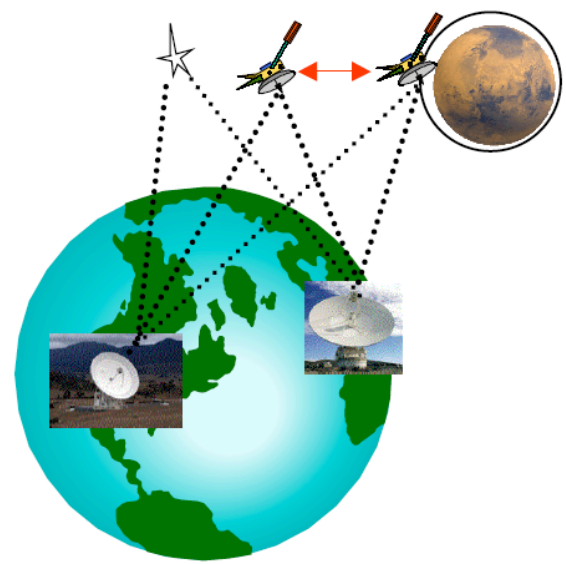
2008
OSTM



>12 years of on-orbit performance

Deep Space Tracking

- Challenges of deep space tracking from Earth
  - Weak signals
    - NASA Deep Space Network uses 70-m and 34-m antennas
  - Geometry and visibility
  - Light travel time from Earth
    - 5 to 25 minutes to Mars
    - ~ 1.3 sec to Moon
  - Reference frame issues
- Typical data types
  - Two-way Doppler, 0.03 mm/s
  - Two-way range, 2 meters
  - Delta-Differential one-way range, VLBI
    - 2 nrad = 0.06 nsec = 1.2 cm delay
  - Optical navigation



Applications of Clocks to Space Navigation & “Planetary GPS”

“In Situ” Tracking at Other Planetary Bodies

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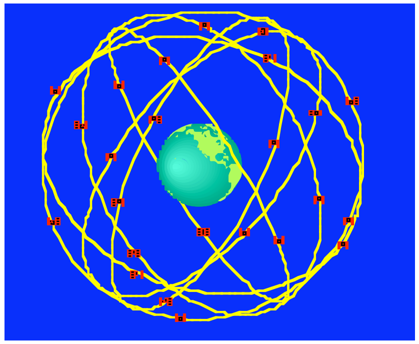
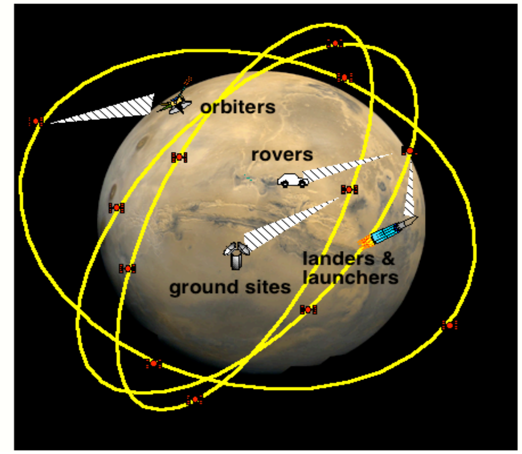
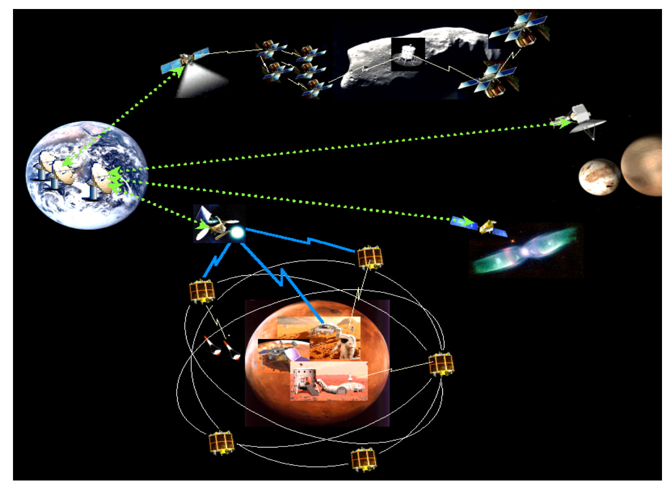


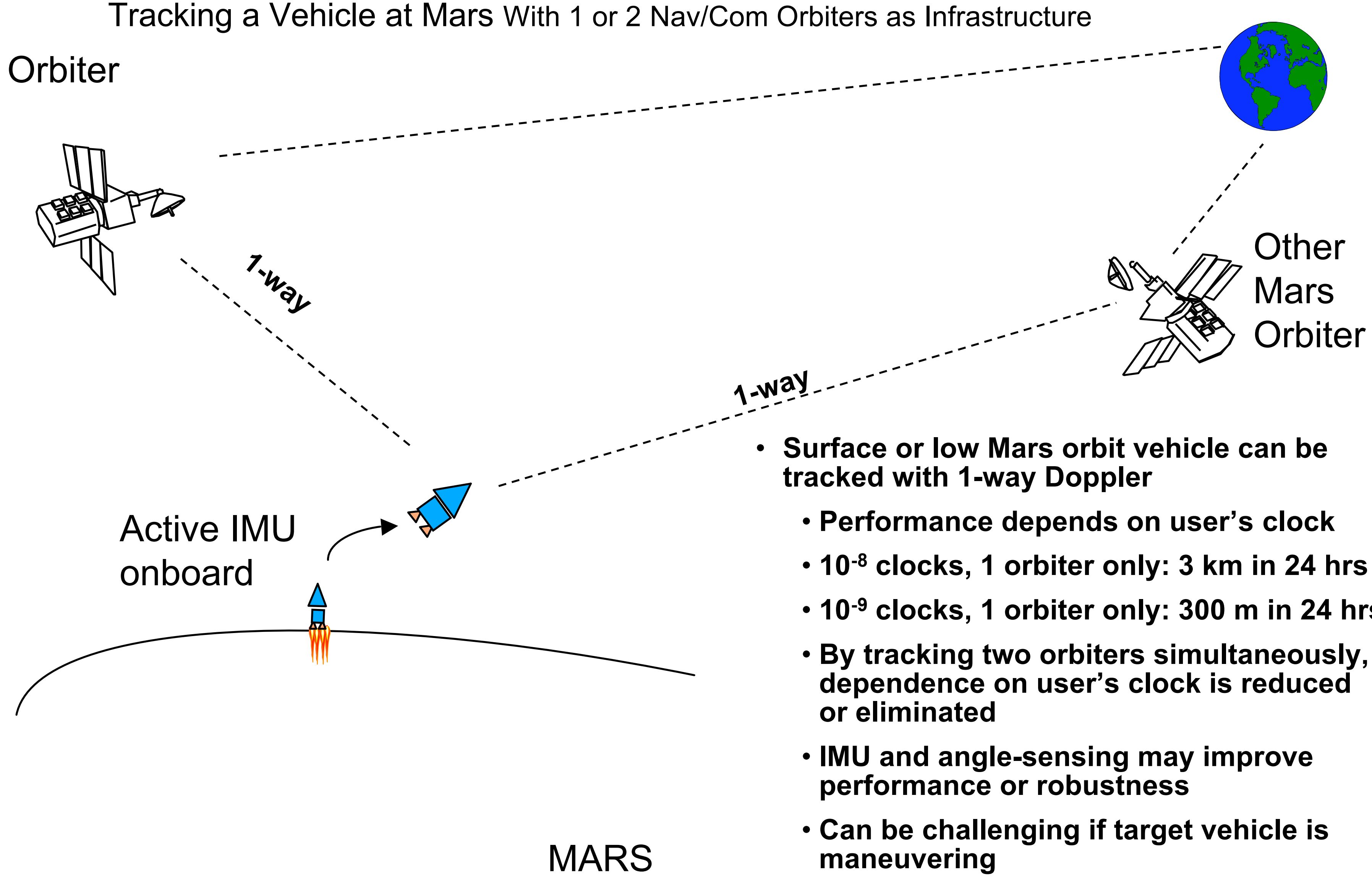




- **The MER mission dramatically proved the high value of having navigation & telecom “infrastructure” during challenging surface operations on other planetary bodies**
- **What is the best approach for Mars? For the Moon?**
  - **Light travel time to Mars is tens of min, but only about 1 sec to the Moon**
    - **Importance of autonomy**
  - **Some Earth-orbiting GPS can be usefully tracked at Moon**

Applications of Clocks to Space Navigation & “Planetary GPS”

Tracking a Vehicle at Mars With 1 or 2 Nav/Com Orbiters as Infrastructure



- Surface or low Mars orbit vehicle can be tracked with 1-way Doppler
  - Performance depends on user’s clock
  - 10^{-8} clocks, 1 orbiter only: 3 km in 24 hrs
  - 10^{-9} clocks, 1 orbiter only: 300 m in 24 hrs
  - By tracking two orbiters simultaneously, dependence on user’s clock is reduced or eliminated
  - IMU and angle-sensing may improve performance or robustness
  - Can be challenging if target vehicle is maneuvering

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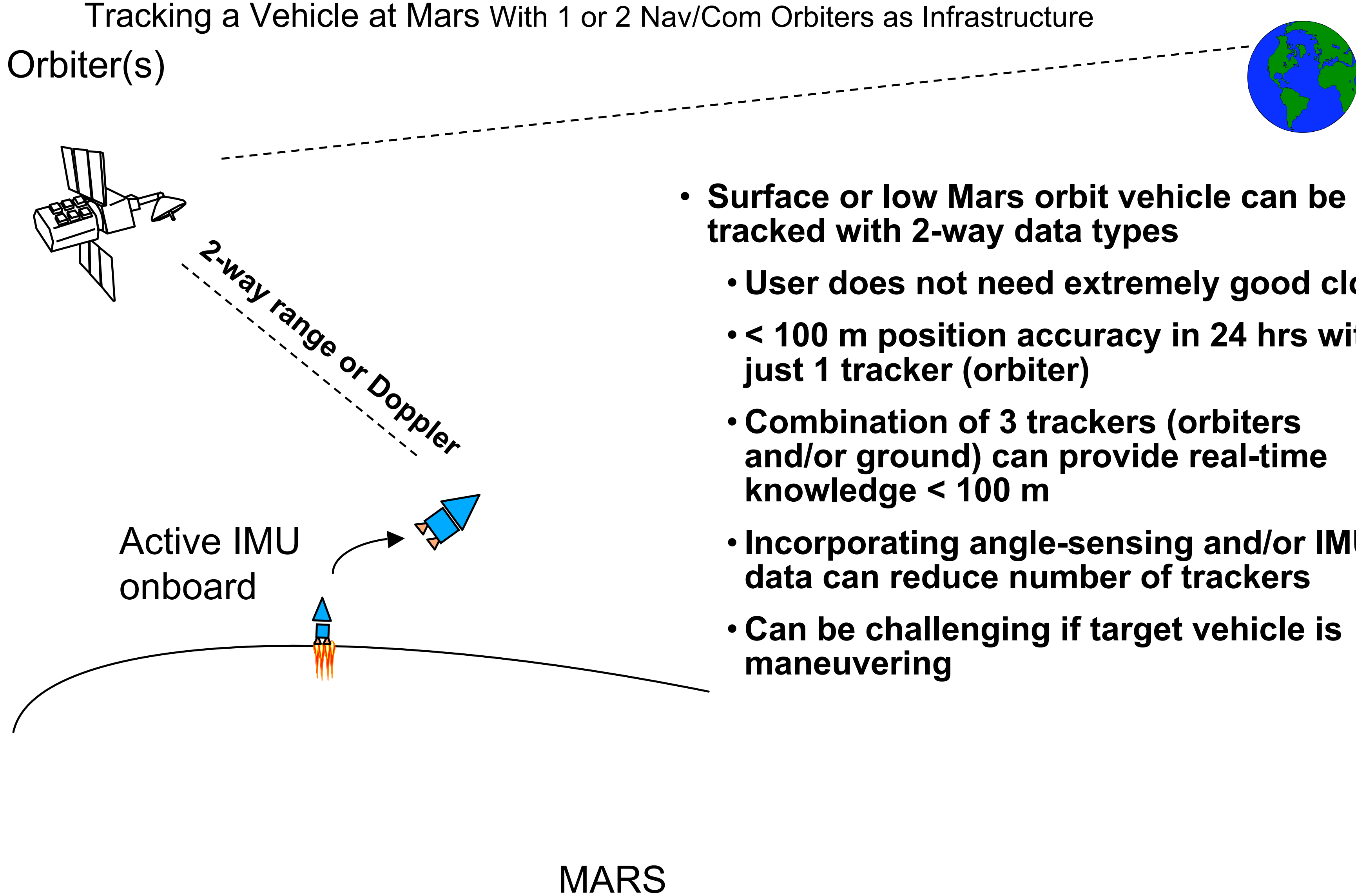
Tracking a Vehicle at Mars With 1 or 2 Nav/Com Orbiters as Infrastructure

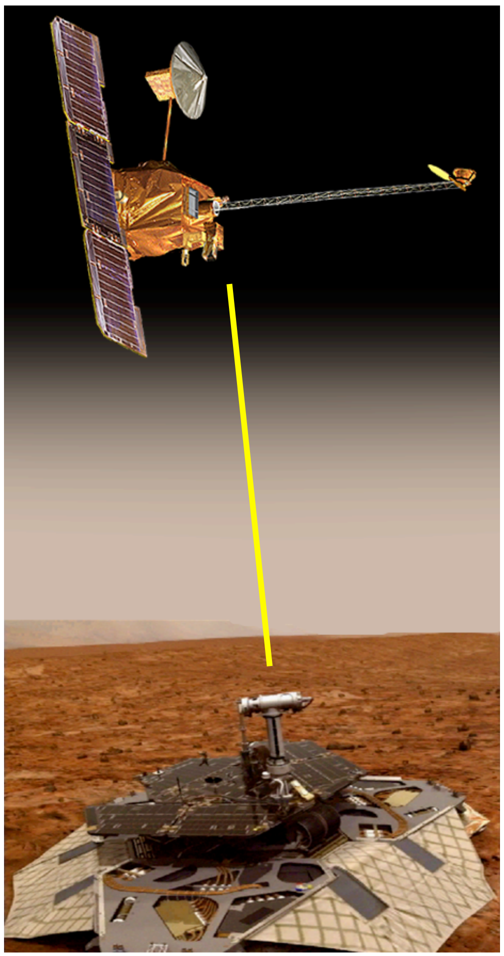


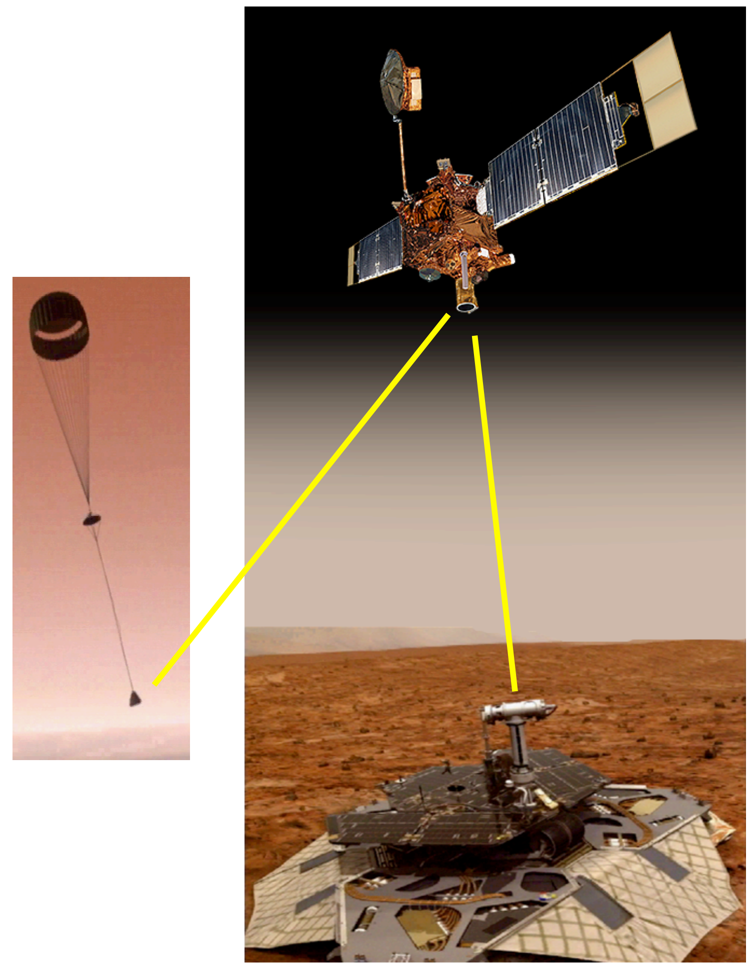
- **Surface or low Mars orbit vehicle can be tracked with 2-way data types**
  - **User does not need extremely good clock**
  - **< 100 m position accuracy in 24 hrs with just 1 tracker (orbiter)**
  - **Combination of 3 trackers (orbiters and/or ground) can provide real-time knowledge < 100 m**
  - **Incorporating angle-sensing and/or IMU data can reduce number of trackers**
  - **Can be challenging if target vehicle is maneuvering**

Applications of Clocks to Space Navigation & “Planetary GPS”

MER Tracking via Odyssey and MGS

- **Two-way Doppler tracking was successful between the landed MER and Odyssey. A position was eventually determined (days later) accurate to tens of meters.**
- **One-way Doppler tracking was successful between MER and MGS *during and after* the critical Entry/Descent/Landing.**





Applications of Clocks to Space Navigation & “Planetary GPS”

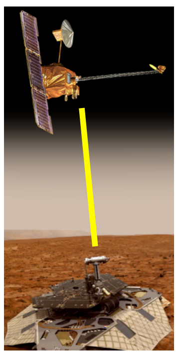
- Three key approaches to navigation/telecom infrastructure assets in Lunar or Martian regimes

  1. **Rely on simpler data types such as 2-way or 1-way Doppler with “orbiters of opportunity,” i.e., existing orbiting vehicles (as was done with MER)**
  2. **Deploy a sparser version of a GPS-like constellation. Provide Navigation services similar to how GPS does at Earth. Same space vehicles can also provide Telecommunications services.**
  3. **Deploy constellation utilizing dual one-way tracking between infrastructure assets and users, which must be equipped with compatible navigation/telecom transceivers.**

Applications of Clocks to Space Navigation & “Planetary GPS”

- Three key approaches to navigation/telecom infrastructure assets in Lunar or Martian regimes (cont.)

1. Rely on simpler data types such as 2-way or 1-way Doppler with “orbiters of opportunity,” i.e., existing orbiting vehicles (as was done with MER)



- Advantages
  - No new technology; uses whatever orbiters are there (lowers cost)
  - Good user space clocks not needed (lowers cost).
    - Typically, long-term orbiters carry USOs.
- Disadvantages
  - Poorer performance (tens of meters to kilometers after ~ days)
  - Real-time is not easily done with Doppler, since time history is needed to infer dynamics. Cannot easily track irregularly maneuvering vehicles.
  - Uses whatever orbiters are there -- not available on demand. Won’t be immediately available for emergencies.

Applications of Clocks to Space Navigation & "Planetary GPS"

- Three key approaches to navigation/telecom infrastructure assets in Lunar or Martian regimes (cont.)

  2. Deploy a sparser version of a GPS-like constellation. Provide Navigation services similar to how GPS does at Earth. Same space vehicles can also provide Telecommunications services.

  – Advantages
    – High performance possible, depending on coverage/visibility and clock quality
    – Real-time emergency services possible

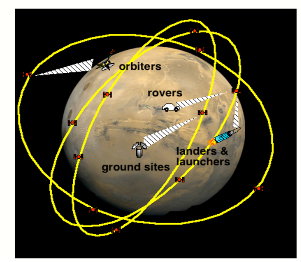
  – Disadvantages
    – Higher cost for operating infrastructure assets (dedicated constellation) at Moon or Mars
    – Higher cost and complexity for utilizing high quality space clocks (as with GPS)

– Technology challenges …

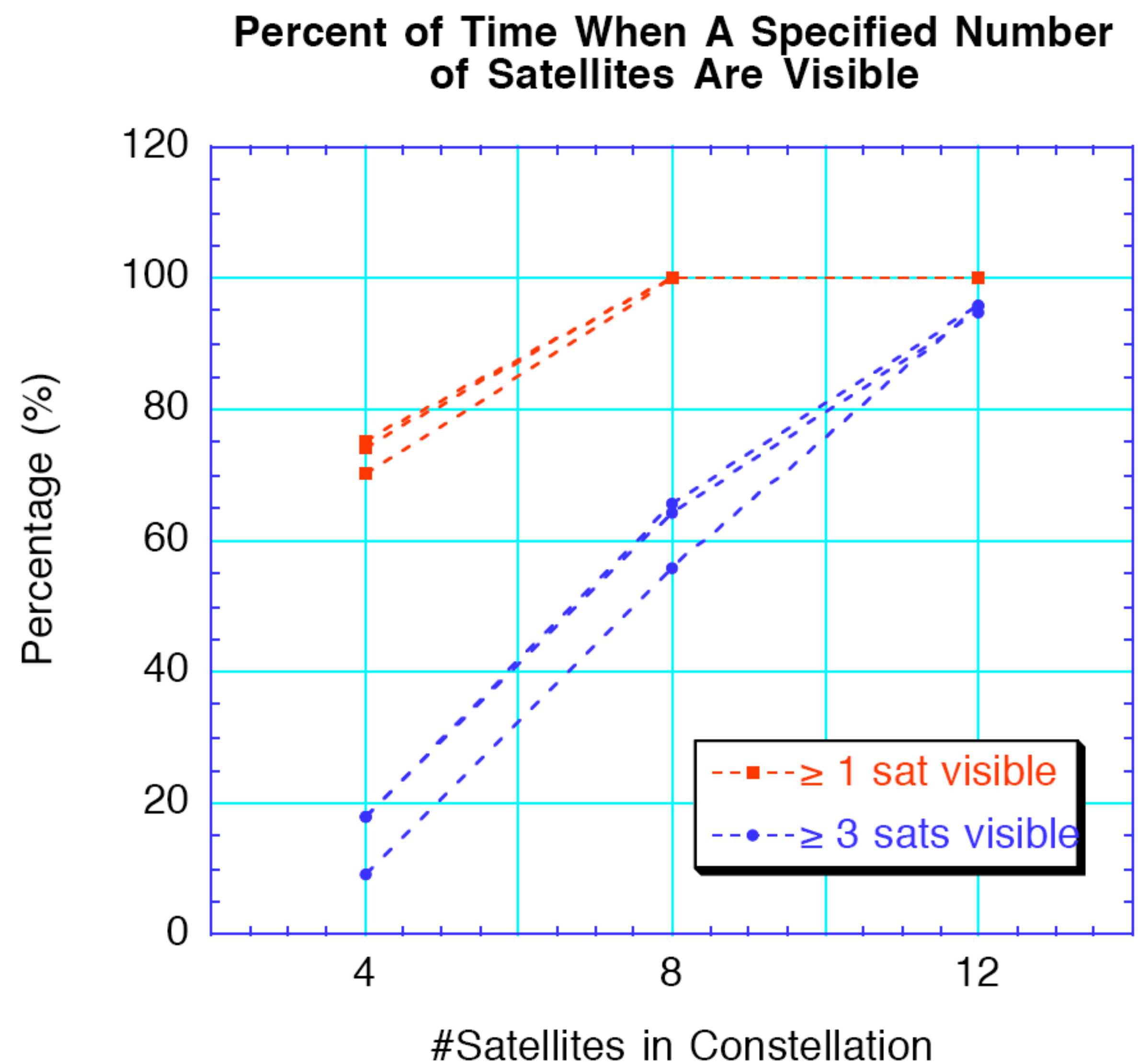
  - Availability/coverage determined by sparseness of constellation

  – Small, cheap very stable space clocks to deploy on infrastructure and users
    – Combination of better clocks + IMU can compensate for coverage "gaps"

  – Develop a cost effective concept of operations.
    – Key trade: should ground tracking terminals be remotely deployed (as are used for GPS operations)? If so, should they be equipped with highly stable clocks? How long can/will such ground automated ground terminals function in a hostile environment? Can the system be maintained solely via Earth tracking? How would the reference frame tie be maintained?



- Results of a simulation performed to evaluate tracking coverage for a Mars network of low-altitude orbiters



Applications of Clocks to Space Navigation & "Planetary GPS"

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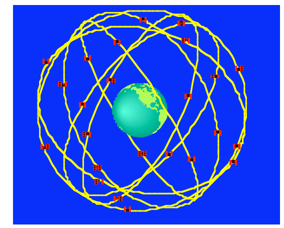
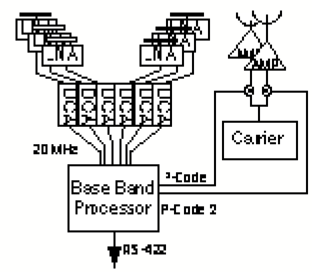
- Three key approaches to navigation/telecom infrastructure assets in Lunar or Martian regimes (cont.)

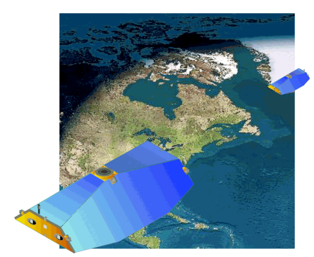
3. **Deploy constellation utilizing dual one-way tracking between infrastructure assets and users, which must be equipped with compatible navigation/telecom transceivers.**
   - Advantages
     - Real-time high (sub-meter) accuracy (if coverage is adequate)
     - Smaller number of good space clocks needed because system relies on dual-one-way tracking data (insensitive to clocks)
   - Disadvantages
     - Self-jamming (transceivers transmitting and receiving simultaneously)
     - System complexity for scalability to many simultaneous vehicles/users
     - Users must carry compatible transceivers
   - Role of clocks
     - Good clocks not required for precise ranging between spacecraft, but at least one to several long-term stable and precise space clocks are required to maintain system timing and reference frame registration (equivalent to knowledge of UT1-UTC at Earth).
     - Without these stable clocks, system autonomy will not be possible and system operation will be more complex and costlier



Advanced GPS flight receivers for Earth, atmospheric, and ocean science and for precise navigation.



Autonomous Formation Flyer (AFF) and Software Reconfigurable Radio/Transceivers for integrated deep-space navigation/telecom and formation flying.



GRACE combines space GPS plus ultra-precise (1-micron delta-range) inter-spacecraft transceivers

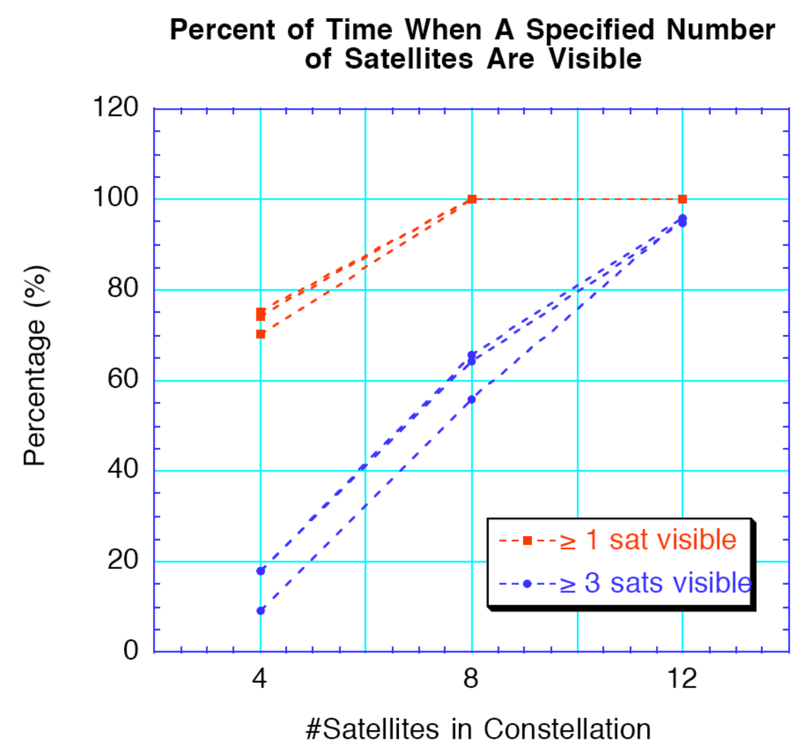
Summary

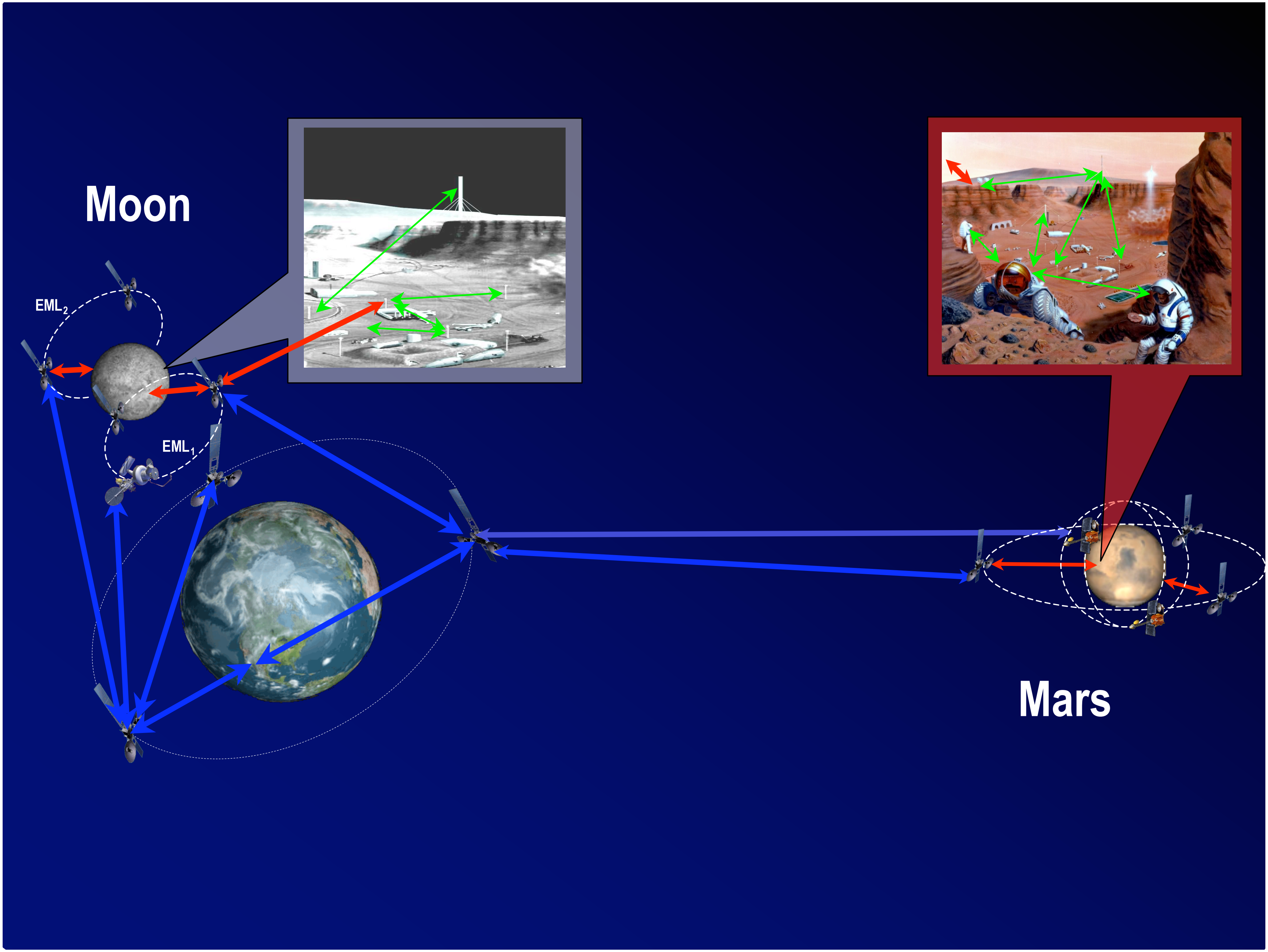
- The ability to fly atomic clocks on GPS satellites has profoundly defined the capabilities and limitations of GPS in near-Earth applications
- It is likely that future infrastructure for Lunar and Mars applications will be constrained by financial factors
- The development of a low cost, small, high performance space clock -- or ultra-high performance space clocks -- could revolutionize and drive the entire approach to GPS-like systems at the Moon (or Mars), and possibly even change the future of GPS at Earth
- Many system trade studies are required. The performance of future GPS-like tracking systems at the Moon or Mars will depend critically on clock performance, availability of inertial sensors, and constellation coverage.
  - Example: present-day GPS carry 10^{-13} clocks and require several updates per day. With 10^{-15} clocks, a constellation at Mars could operate autonomously with updates just once per month.
- Use of GPS tracking at the Moon should be evaluated in a technical study.

Applications of Clocks to Space Navigation & "Planetary GPS"
Summary (cont.)

- **Next steps:** Develop a program to perform simulations and experiments to evaluate and compare capabilities and costs for the different navigation/telecom scenarios for Moon and Mars infrastructure

- Determine how precise/stable flight clocks and IMU sensors can "fill in" coverage gaps for sparser versions of GPS
  - Goal is to determine how GPS-like capabilities can be enabled with fewer than 4 "GPS" in view
    - How long and how accurately can positioning be sustained with 3, 2, 1 or even 0 orbiters in view?
  - Use current GPS terrestrial and space data to perform tests and experiments. Excellent data sets and test facilities are available.
    - Evaluate clocks and IMU sensors over a wide range of performance
  - Evaluate different concepts of operations
    - What is the value of an extremely accurate ground clock at Mars or Moon? How survivable is a ground clock, versus a space clock in an orbiter? Does the ground clock enable simplification of the orbiting payloads? Is the trade worthwhile?
- Evaluate GPS tracking at the Moon and how coverage might be extended to the far side




Moon
EML2
EML1
Mars