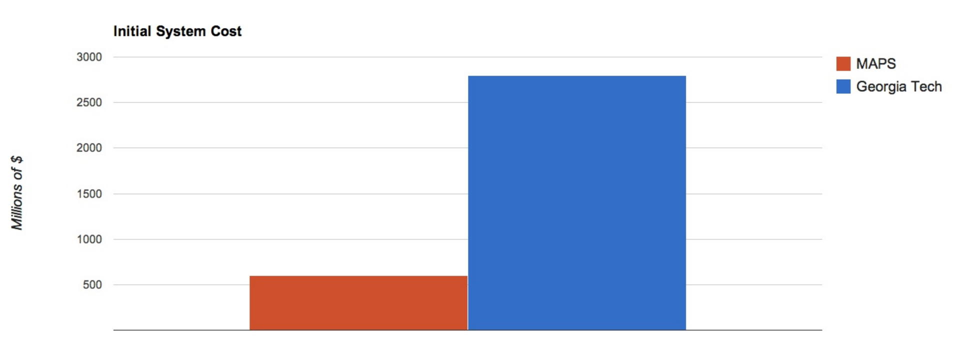
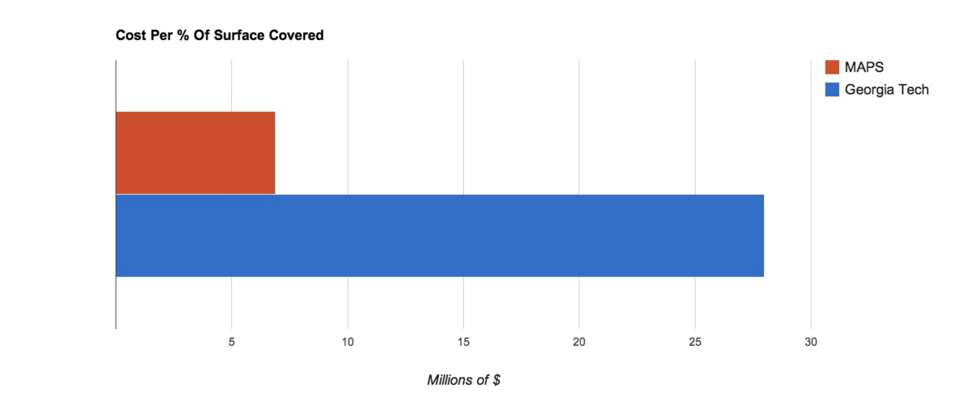
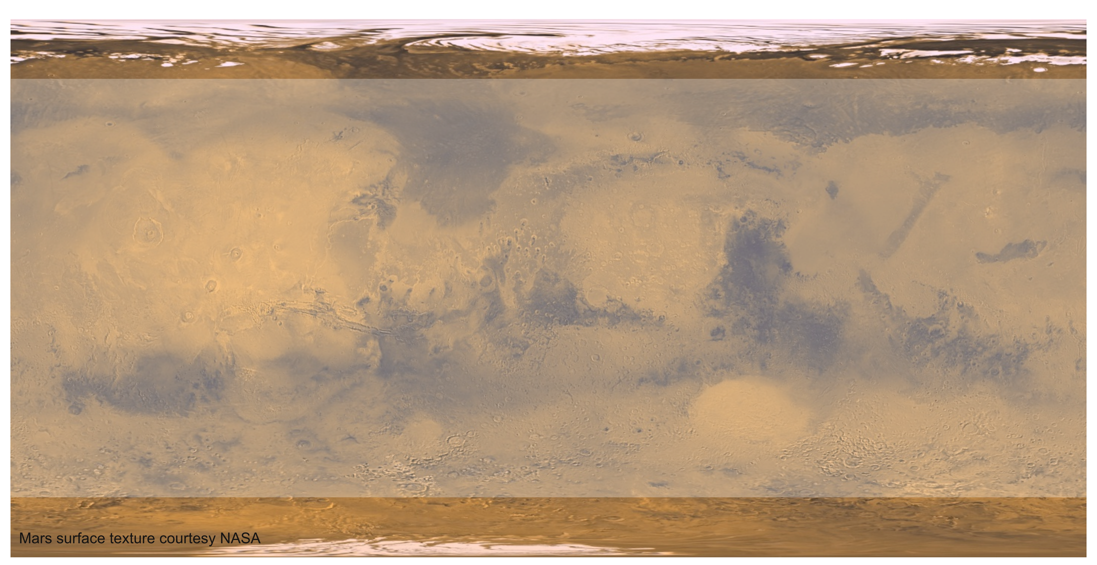
Mars Absolute Positioning System (MAPS)

Summary

Over the past few decades, Mars has become the focal point of robotic space exploration. One active area of development is that of entry, descent, and landing (EDL) accuracy and precision. A GPS system for Mars is one fitting solution. This project developed a complete GPS system for Mars that provides excellent coverage and is less than a quarter the price of an alternative system outlined by Georgia Tech.







MAPS system coverage map. Lighter band represents areas which receive coverage 100% of the time (70ºN to 70ºS).

Problem

Spacecraft on Mars need an accurate method of determining their precise location. The system must provide adequate coverage of the planet's surface to service as many rovers and landers as possible. Above all, however, the solution must be economical, not requiring billions of dollars to be accomplished.

Design Criteria

Design a realistic GPS system for Mars including:

- Satellite configuration
- Spacecraft design
- Mission timeline for system installation

The design must achieve:

- High percentage of surface coverage
- Lower cost than alternative solutions
  (Georgia Tech's Red Planet Project: $2.8B)

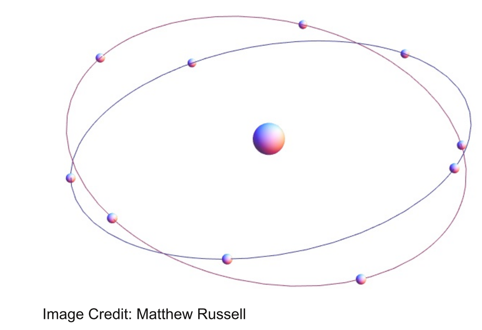
System Development

Satellite Configuration

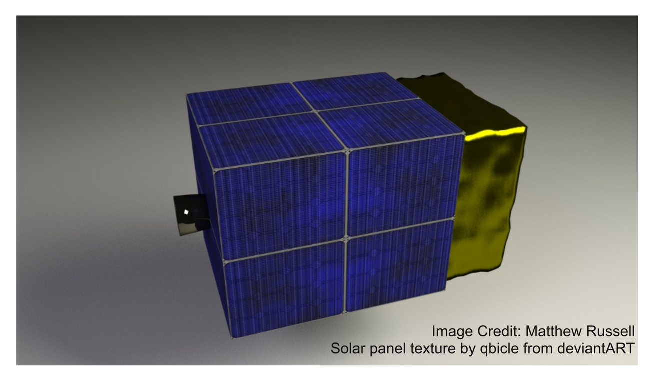
The satellite configuration developed for the MAPS mission achieves coverage 100% of the time for 87% of the surface, including all but one of the rovers and landers ever sent to Mars. The configuration was originally taken from Georgia Tech's Red Planet Project but was adapted using a custom Python program to better fit the MAPS mission design. The software simulates the system until all the satellites have returned to their initial positions, evaluating at each time-step if enough satellites are in view for a location fix. To create a more user-friendly interface, an HTML5 web application was later developed.

Technical Specifications

# of Constellations: 2
Satellites per Constellation: 5
Inclination: 10°
Period: 3 Martian days
Altitude: 39,100 km
Coverage: 87%



MAPS Navigation Satellite



Technical Specifications

Dimensions: 0.65 x 0.40 x 0.40 m
Dry Mass: 53 kg
Liftoff Mass: 70 kg
Thruster: Daimler-Benz CHT 400
Propellant: Hydrazine
Navigation Clocks: 3 Deep Space Atomic Clocks

The design for the navigation satellites was constructed by researching the typical components required for spacecraft and incorporating the additional components, such as atomic clocks, which would be required for use in a GPS system. The clock selected for this project was the Deep Space Atomic Clock (DSAC) because of its small size and low mass. A single Daimler-Benz CHT 400 thruster generates the force to circularize the satellite's orbit upon being released from the transport vehicle.

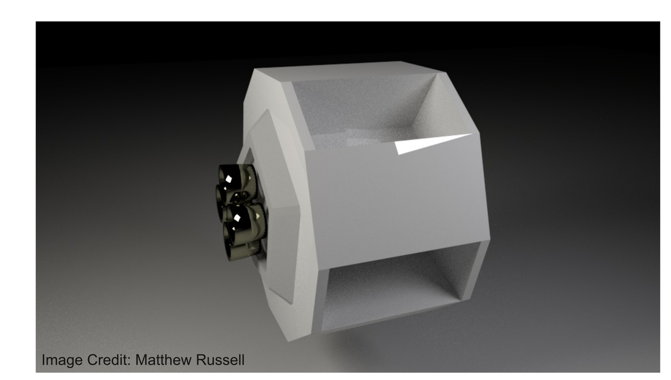
Due to its similarity in size and mass to the Surrey Satellite SSTL-150 platform, the cost of each navigation satellite was estimated to be $17 million.

Satellite Transport Vehicle (STV)

The core of the mission is the Satellite Transport Vehicle, a 1.7 m diameter spacecraft containing five MAPS navigation satellites. This spacecraft will attach onto another mission traveling to Mars in order to conserve the cost of using separate launches. It has four Daimler-Benz S400/1 thrusters for orbital insertion and inclination change. By comparing the STV to the Mars Atmosphere and Volatile Evolution (MAVEN) spacecraft, the dry mass of the Satellite Transport Vehicle was estimated to be 250 kg. The cost will be approximately $200 million.

Technical Specifications

Dimensions: 1.7 x 1.6 x 1.35 m
Dry Mass: 250 kg
Liftoff Mass: 430 kg (w/o MAPS satellites)
Thrusters: 4 Daimler-Benz S400/1
Fuel: Monomethylhydrazine
Oxidizer: N_2O_4

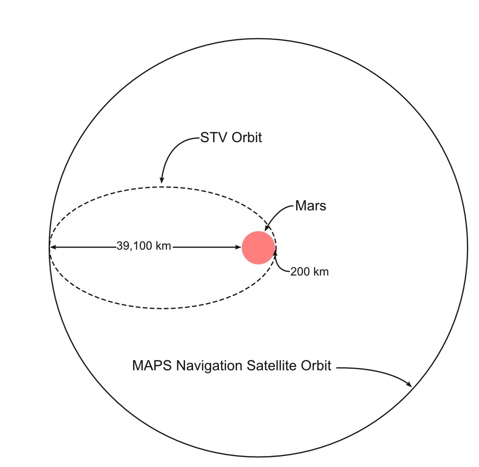


Mission Timeline

After designing and evaluating two different mission timelines for mass requirements and ease of implementation, an innovative outline was chosen for the MAPS system installation.

1. STV is loaded with five navigation satellites and attached onto the primary mission spacecraft. STV separates from primary mission upon reaching Mars.
2. STV is captured into a highly elliptical equatorial orbit around Mars with a periapsis of 200 km and an apoapsis of 39,100 km.
3. STV adjusts its orbit to reach the desired 10° inclination.
4. Each time the STV reaches its apoapsis it releases one MAPS navigation satellite.
5. Each navigation satellite accelerates upon its release from the STV to circularize its orbit at an altitude of 39,100 km.

These steps will position five navigation satellites into one of the two constellations in the MAPS system. A second mission will complete the system by placing five additional satellites in the final constellation.



Delta-V & Propellant

To complete the mass estimate for one mission, including the STV loaded with five MAPS navigation satellites, the delta-v requirement for each spacecraft was calculated and then converted to propellant mass using the Rocket Equation, resulting in a total mission liftoff mass of 780 kg. The velocities before and after key maneuvers were calculated in order to compute the total delta-v budget for the mission. Adding the magnitudes of these changes resulted in delta-v budgets for both the STV and each navigation satellite. In the following equations, *G* is the universal gravitational constant ($6.67 \times 10^{-11}\ m^3 \cdot kg^{-1} \cdot s^{-2}$) and *M* is the mass of Mars (6.42×10^{23} kg).

$$v = \sqrt{GM\left(\frac{2}{r} - \frac{2}{r_a + r_p}\right)}$$

Speed of spacecraft at distance r in an orbit with periapsis radius r_p and apoapsis radius r_a

$$v = \sqrt{\frac{GM}{r}}$$

Speed of spacecraft in an orbit with radius r

$$\Delta v = v_i \sqrt{2 - 2\cos(\Delta i)}$$

Magnitude of delta-v required for inclination change of Δi degrees with an initial velocity of v_i

Delta-V Budgets

STV: 780 m/s
MAPS Satellite: 610 m/s

The Rocket Equation, solved for m_{prop}, was then used to compute the amount of propellant required for the STV and each navigation satellite.

$$\Delta v = v_{ex} \ln\left(\frac{m_{dry} + m_{prop}}{m_{dry}}\right)$$

The Rocket Equation

$$m_{prop} = m_{dry}\left(e^{\Delta v / v_{ex}} - 1\right)$$

The Rocket Equation, solved for m_{prop}

Propellant Mass

STV: 180 kg
MAPS Satellite: 17 kg

Analysis

By comparing the combined mass of a mission including both the STV and a research satellite similar to MAVEN to the mass of other missions to Mars, this project was able to verify that the combined mission mass would still be within the payload capability of a typical launch vehicle. The total mass of an STV+MAVEN mission would be about 3230 kg, over 600 kg less than the mass of the Mars Science Laboratory (MSL) mission. Because the MSL mission launched on a larger variant of the Atlas V than the MAVEN mission, an additional $7.7 million may be required to upgrade the launch vehicle from the smaller 401 variant to the 541 variant (due to the extra mass of the STV). This is not an unreasonable amount given the overall cost savings of launching two missions at one time.

The cost of each mission is estimated to be $293 million, giving a total cost for the entire system of approximately $600 million, less than a quarter the price of Georgia Tech's proposal.

Validation

The General Mission Analysis Tool (GMAT) developed by NASA was used to simulate the MAPS mission and validate the overall mission design. A basic Earth-Mars mission was used as a foundation, and the additional manuevers required to install one of the MAPS satellite constellations were incorporated to form a complete simulation. This simulation was successful and confirmed the plausibility of the mission concept in a typical scenario.

Conclusion

Spacecraft on Mars need an accurate way to navigate. A GPS-type system would allow landers and rovers to precisely monitor their location during entry, descent, and landing, ensuring that they land exactly at the target position. The improved precision will enable spacecraft to explore areas *previously unreachable* due to dangerous terrain. This project proposes a novel solution which utilizes a Satellite Transport Vehicle to carry five small navigation satellites to Mars while attached to another mission. This unique idea would conserve millions of dollars that would have been spent on separate launches. The solution was validated using NASA's General Mission Analysis Tool and was shown to be well within the payload capacity of the required launch vehicle. **The system provides excellent coverage for the surface of Mars and is less than a fourth the cost of a GPS system outlined by Georgia Tech.**

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