Geophysical Network Mission
for
MARS

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for NetSAG

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Outline

- Science goals and priorities

- Measurement approaches

- Number of stations

- Lifetime

Science Goals and Priorities for a
Mars Network Mission

Network Mission Directly Addresses 2003 Decadal Survey Themes

- **The chapter on the inner solar system identified three unifying themes:**
  - What led to the unique character of our home planet (the past)?
  - What common dynamic processes shape Earth-like planets (the present)?
  - What fate awaits Earth's environment and those of the other terrestrial planets (the future)?
- **Planetary interior and surface meteorology investigations feature prominently in all three of these themes.**

Impact of Mars Interior Studies on Planetary Science

- The interior of a planet retains the signature of its origin and subsequent evolution.
    - Interior processes have shaped the surface of the planet we see today.
- It participates in virtually all dynamic systems of a planet.
    - Source and/or sink for energy, materials
- It provides the "background" against which biomarkers must be measured.
- We have information on the interiors of only two (closely related) terrestrial planets, Earth and its Moon.
    - Observing another planet (any planet!) will provide enormous advances in our understanding of the history of the solar system and planetary processes.
- **However, Mars provides a unique opportunity:**
    - Its surface is much more accessible than Mercury, Venus.
    - Our knowledge of its geology, chemistry, climate history provides a rich scientific context for using interior information to increase our understanding of the solar system.

Example: Implications for Early Planetary History

- **Provides insight into initial accretion composition and conditions**
  - Accreting planetesimals determine planetary composition and influence its oxidation state
    - A highly reducing mantle will retain carbon for later degassing
  - Speed of the accretion process governs the degree of initial global melting
    - Accretion without initial melting may produce earlier, more vigorous convection, eliminating regional compositional variations
- **Retains the signature of early differentiation processes**
  - Partitioning of sulfur and other alloying elements between core and mantle
  - Partitioning of iron between the silicate mantle and metallic core
  - Magma ocean processes may move late, incompatible-element enriched material to the lower mantle or core boundary
  - Crust, mantle formation: Magma ocean melting, fractionation, and solidification, late-stage overturn
- **Records the effects of subsequent thermal history**
  - Vigorous solid-state convection will tend to remove compositional heterogeneities (which are indicated by SNC compositions)
  - Polymorphic phase boundaries can have large effect on convection
  - Partial melting drives volcanism, upper mantle and crust stratification
    - Can move incompatible-element enriched material into the crust or upper mantle
  - Amount (if any) of core solidification
    - implications for composition and temperature, dynamo start-up and shut-down

Example: Implications for Volatile History

- Thermal evolution controls the timing of volatile release, and influences the availability of water in a liquid state.
  - Volatiles (H_2O, CO_2, CH_4, etc.) are released from the interior to the atmosphere and surface via differentiation and volcanism.
  - The thermal gradient in the crust controls the deepest boundary condition for surface-atmosphere volatile exchange, and the depth to liquid water.
- An early magnetic dynamo may have helped protect the early atmosphere from erosion by solar wind.
- Formation hypotheses for the global dichotomy have different implications for regional crustal volatile contents.

# Other Implications for Planetary Science

- **Chemical evolution of surface rocks**
  - Magma compositions, variation through time
  - Other chemical aspects, such as oxidation state, volatile fraction (including gases such as CO_2, SO_2, CH_4, etc.)
  - Physical properties of lavas, such as temperature, viscosity, effusion rate.
- **The geological heat engine**
  - Drives major surface modification processes: Volcanism, tectonics
  - Determines subsurface hydrological system, extent of cryosphere.
- **Biological potential**
  - Clues to early environment
  - Magnetic shielding from particle radiation
  - Relationship to atmospheric density and composition
  - Geothermal energy
  - Chemical inventory of the crust
- **…**

What Don't we Know About the Interior of Mars?
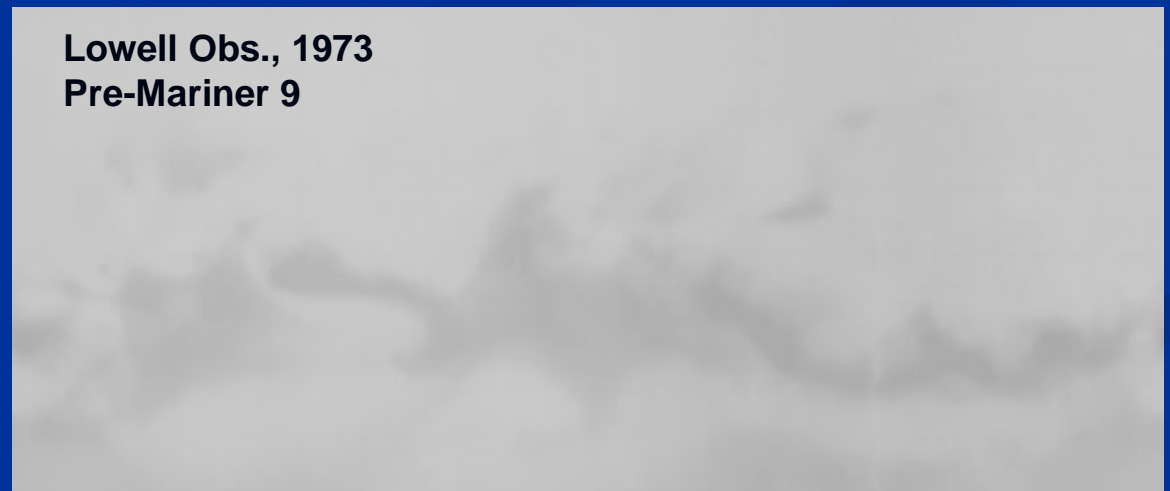
Graphical Analogy: Surface vs. Interior

Looking at the Surface:

11 successful orbital and 5 successful landed missions, umpty-twelve instruments.

MOLA, 2001
Post-MGS
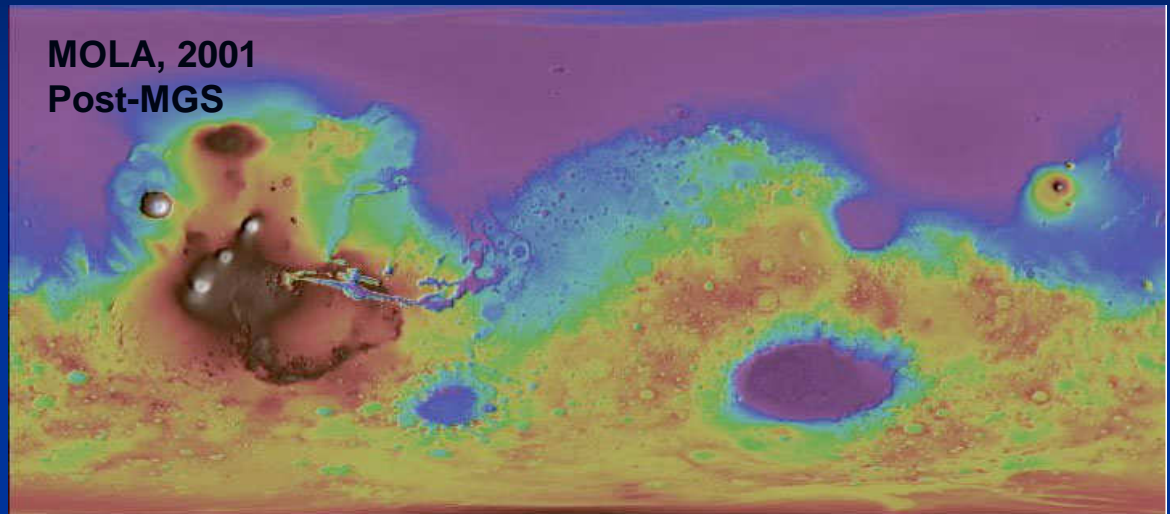
Looking at the Interior:

0 dedicated missions, orbital gravity and magnetic measurements, 1 (limited) surface instrument, some surface tracking, SNC meteorites.

Lowell Obs., 1973
Pre-Mariner 9

Crustal Questions

- **The volume of the crust is unknown to within a factor of two.**

- Does Mars have a layered crust? Is there a primary crust beneath the secondary veneer of basalt?

- To what extent were radiogenic elements concentrated in the crust? Is there a difference in composition between the north and the south?

- Is the crust a result of primary differentiation or of late-stage overturn? How much of it is secondary?


Crustal thickness
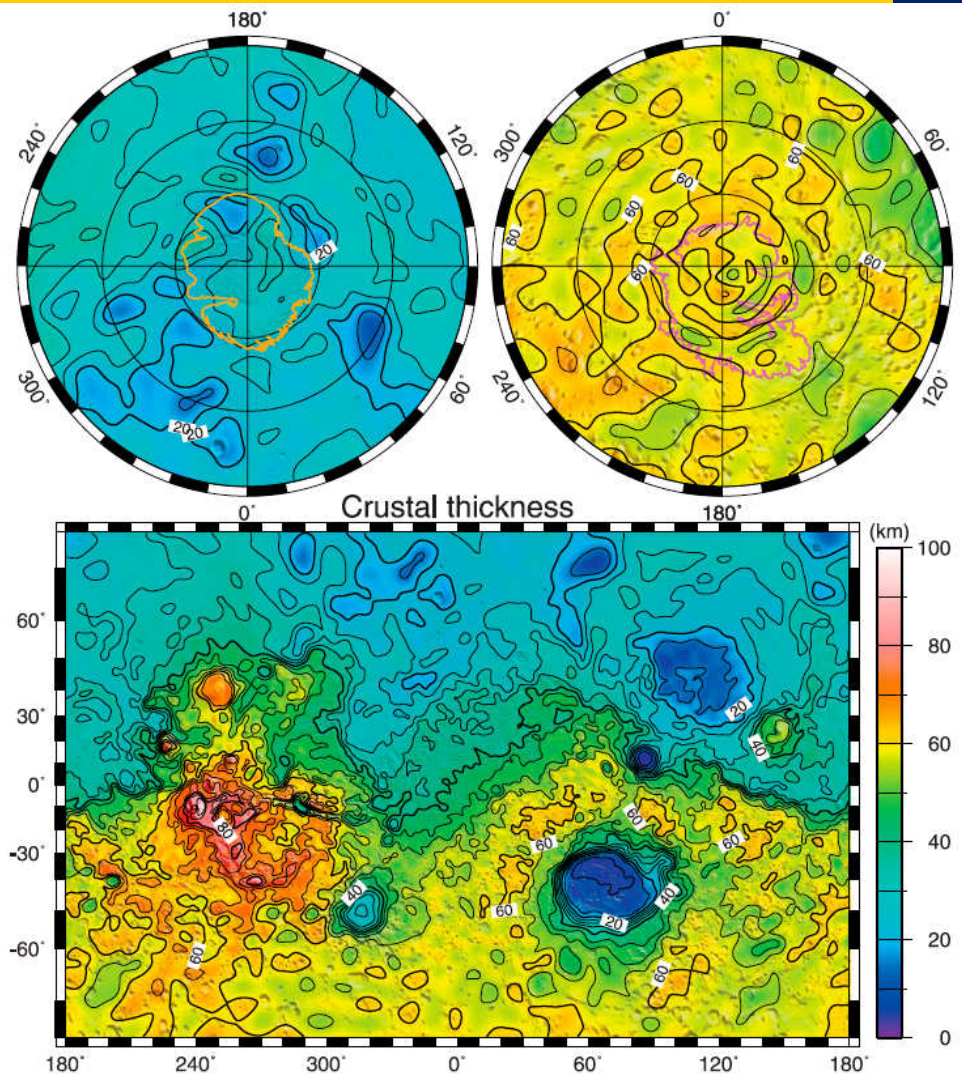
Mantle Questions

- What is the actual mantle composition (e.g., Mg#, mineralogy, volatile content oxidation state)?
- To what degree is it compositionally stratified? What are the implications for mantle convection?
- Are there polymorphic phase transitions?
- What is the thermal state of the mantle?
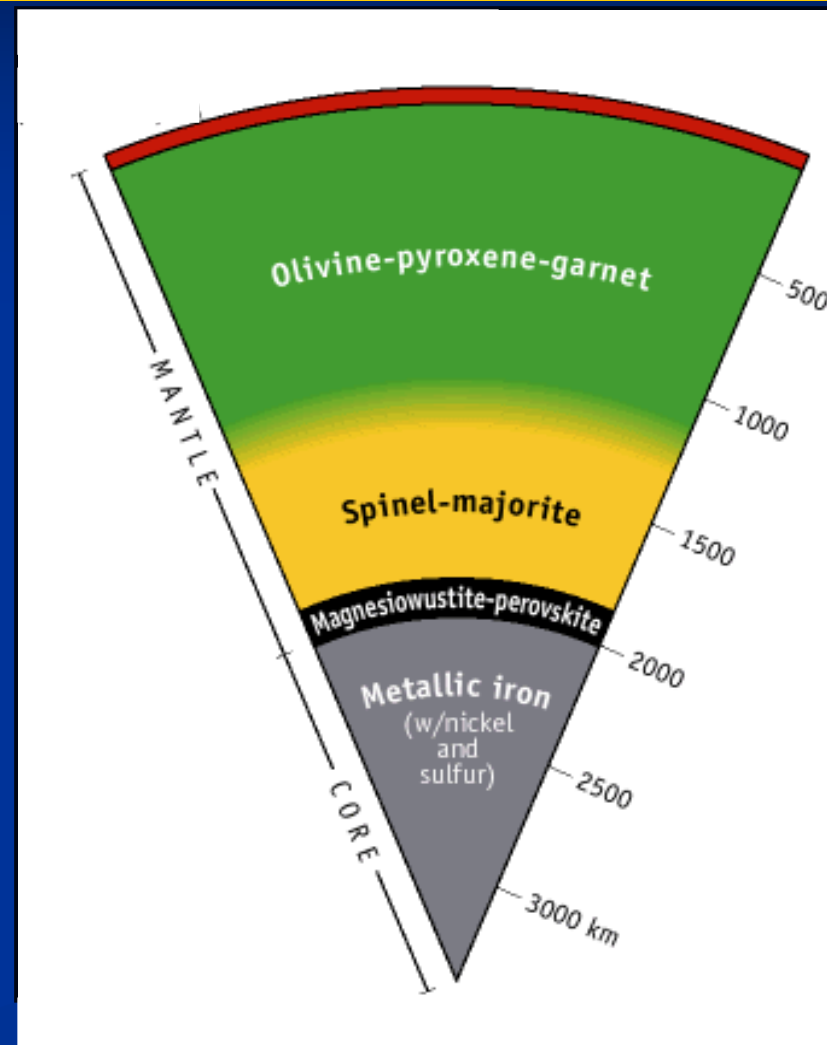
Questions About Core Structure

- Radius is 1600 ±150 km, so density is uncertain to ±20%
- Composed primarily of iron, but what are the lighter alloying elements?
- At least the outer part appears to be liquid; is there a solid inner core?
- How do these parameters relate to the initiation and shut down of the dynamo?
- Does the core radius preclude a lower mantle perovskite transition?
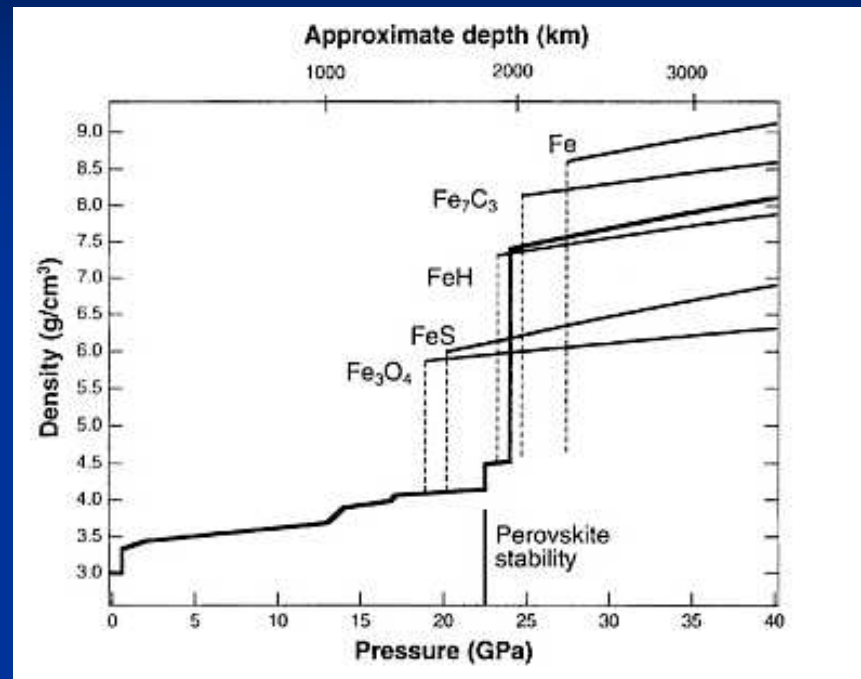
Our only constraints on the core are the moment of inertia and total mass of Mars. But since we have three parameters (mantle density, core radius and density), we are stuck with a family of possible core structures, each with significantly different implications for Mars' origin and history.

Highest Priority Science Goals

- Determine the thickness of the crust at several geologically interesting locations. Determine crustal layering at these locations.

- Determine the depths to mantle phase transition boundaries or compositional boundaries.

- Determine the radius of the core .

- Determine the state of the core and the radius of a potential inner core.

- Determine the additional details of the radial seismic velocity profile of the planet interior.

- Determine the global planetary heat flow.

Network and Climate Objectives

- Characterizing the dynamic range of the climate system requires long-term, global measurements.

- Some key measurements can only be made at the surface.

- The only way to address the highest priority investigations would be with a long-lived global network supported by one or more orbital assets.

- A global meteorological network for monitoring atmospheric circulation would require >16 stations (Haberle and Catling, 1996).

- **Thus this mission would not constitute a "meteorological" network.**

- This type of mission could still make substantial and important progress towards the MEPAG climate goals and objectives.

- **In particular, it could address how the atmosphere and surface interact in regulating the exchange of mass, energy, and momentum at this boundary.**

Other Science on a Network

- There are many science investigations that could benefit from observations at multiple locations on the surface of Mars.

- However, none have been identified that require the unique characteristics of a simultaneous network.

- Our recommendation is that the objectives/payload for a Mars network mission be limited to those focused on the deep interior, with the exception of some level of atmospheric investigation.

# Network Mission Measurements Relating to the Interior - 1

- **Seismology is BY FAR the most effective method for studying the internal structure of a planet.**
    - **Perhaps 90% of what we know of the Earth's interior comes from seismology.**
    - A great deal of our knowledge of the Moon's interior comes from the very limited Apollo seismic experiment.
- **Seismic waves pass through the planet and are affected in a multitude of ways by the material through which they pass:**
    - Speed
    - Direction
    - Amplitude
    - Frequency
    - Polarization
    - Mode partitioning
- **Since they are (an)elastic waves, they respond to the elastic constants, density and attenuation, which can be related to specific rock types, temperature and volatile content.**
- **These effects can be deconvolved to derive the planet's structure.**
- **Each seismic event (marsquake) is like a flashbulb illuminating the inside of the planet.**
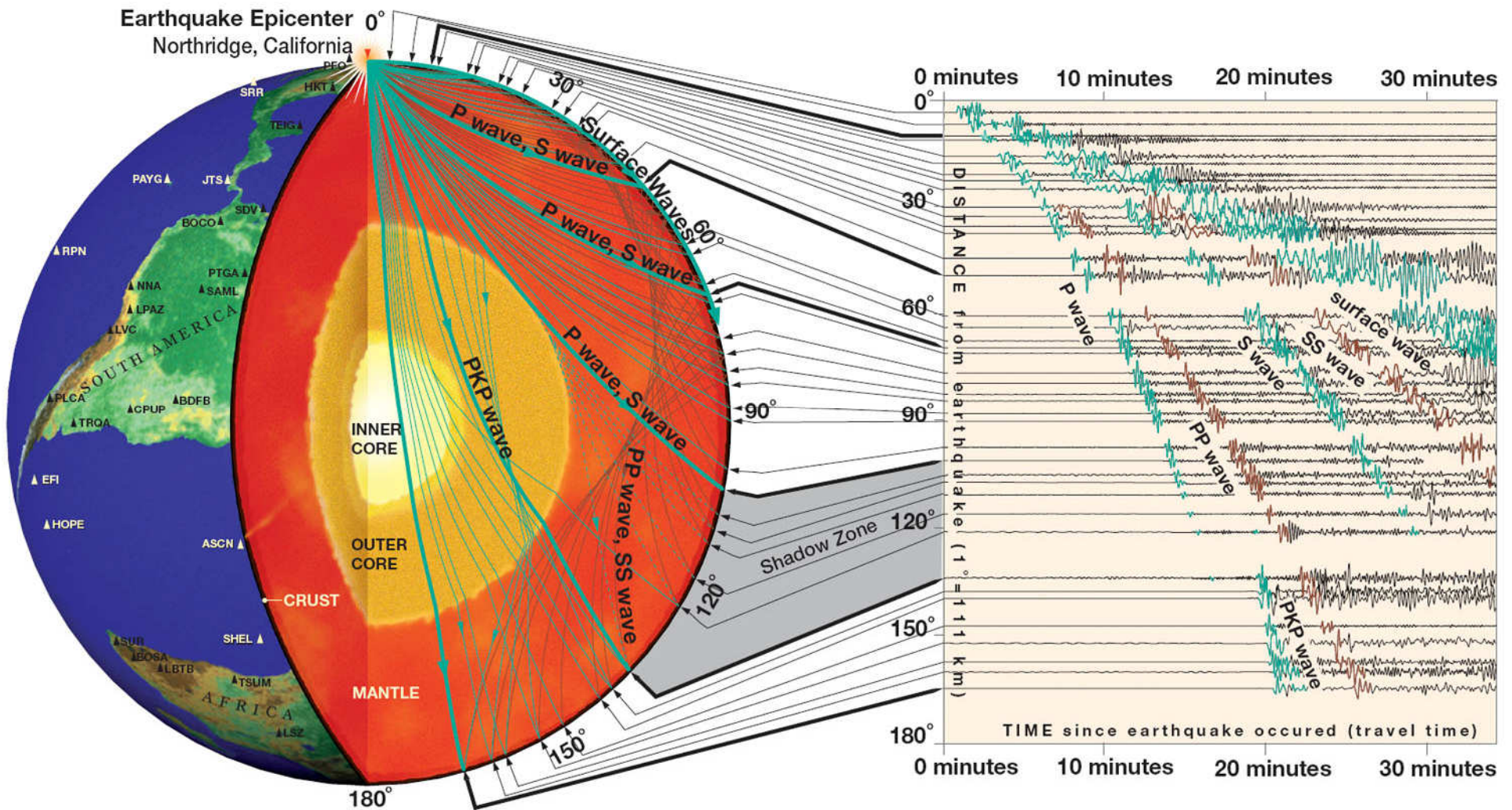
Body Wave Seismology

P   S
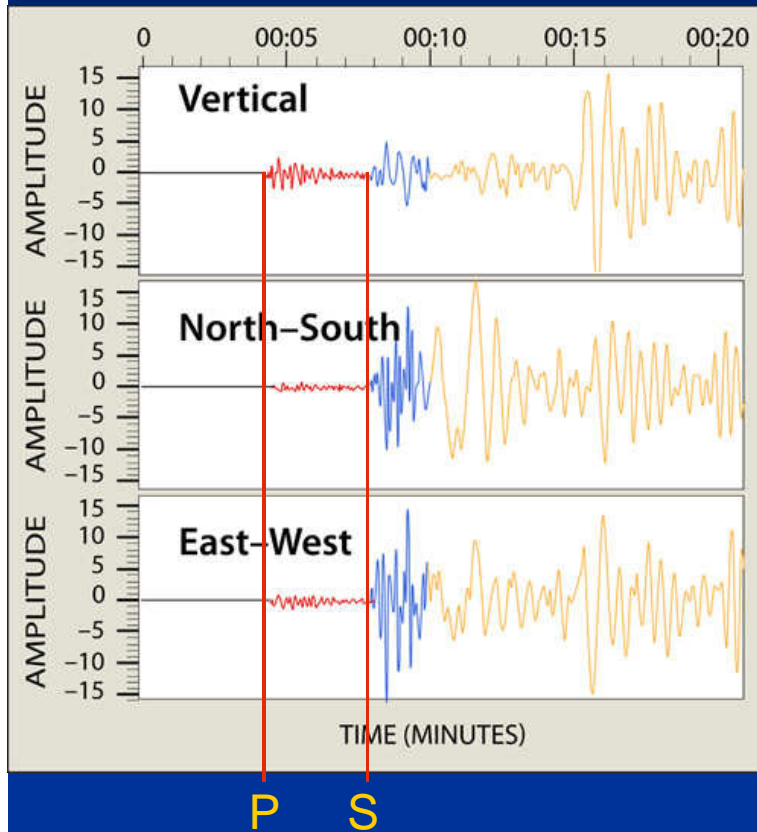
- The most straightforward seismic method is body-wave travel-time analysis.
- Must accumulate events at various distances from the sensor to probe the full range of depths.
- Need lots of events!
- Need to detect each event at 3 or more stations to be able to reliably locate its source

Note that there is considerable science (such as level of geologic activity, tectonic patterns, frequency of meteorite strikes, etc.) just from determining the size and locations of events.
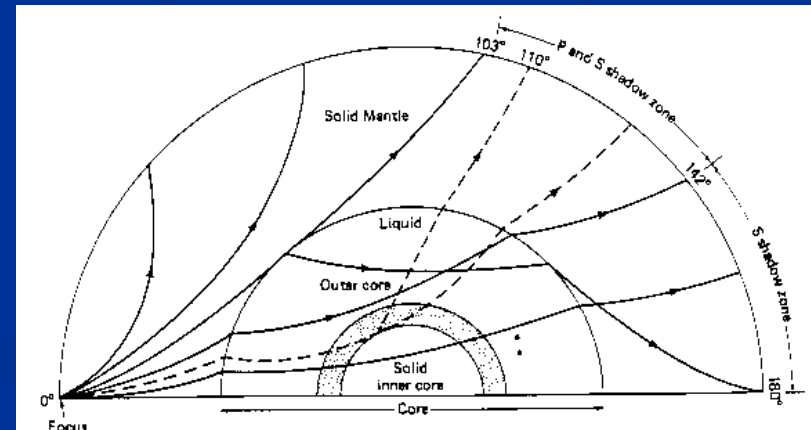
Travel Time Analysis

Body Wave Seismology

- **Each line in the travel-time plot represents a ray that has taken a different path through the planet (including mode conversions P↔S).**
- **The slope of the line gives the apparent wave velocity ($d\Delta/dt$) as a function of distance at the surface; vertical position gives depth to boundaries.**
  - These can be converted into actual wave velocity as a function of depth through the magic of mathematics!
- **Elastic wave velocity depends on material constants k, μ, ρ:**
  - $v_p = [(k+4\mu/3)/\rho]^{1/2}$
  - $v_s = (\mu/\rho)^{1/2}$
- **These can be compared to lab measurements on minerals.**

Mars Synthetic Travel Time Plot
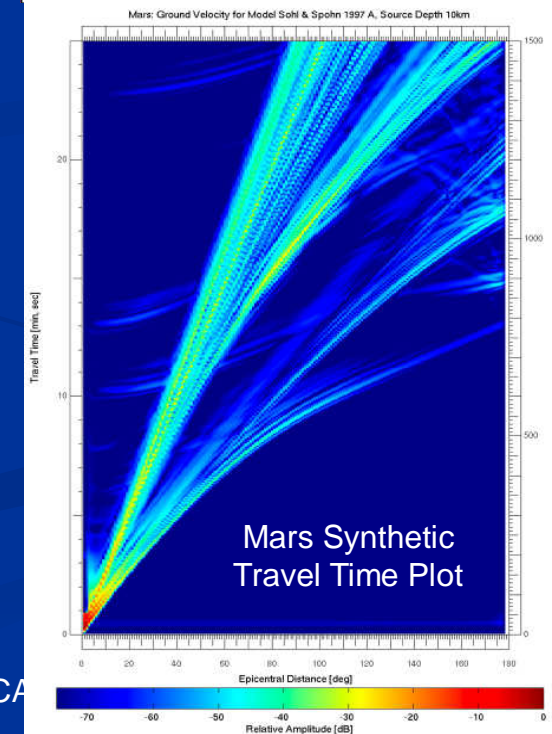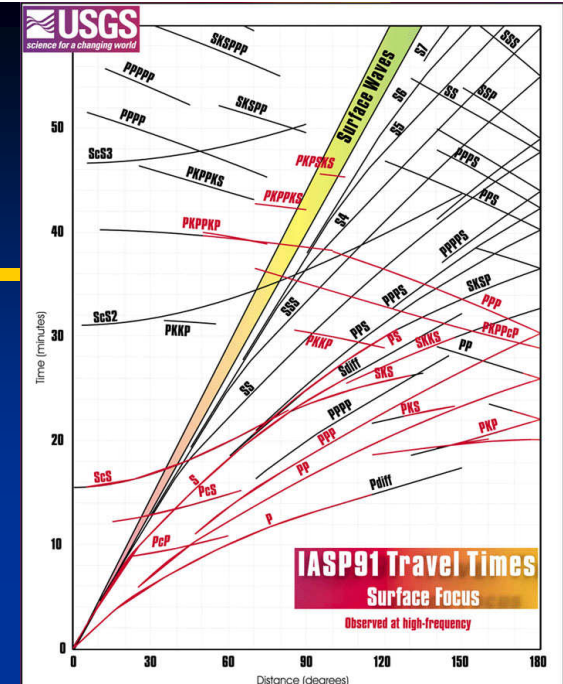
Network Mission Measurements Relating to the Interior - 2

- **Rotational Dynamics (precision tracking)**
  - Variations in the rotation vector (magnitude and direction) can be related to both the radial density structure (dependent on composition) and damping (which derives from viscous response, related to both composition and temperature).
- **Heat Flow**
  - Heat flux from the interior is a crucial boundary condition for determining the thermal state and its history.
- **Electromagnetism**
  - Dipole B field (if any) tells us about core structure (none on Mars)
  - Crustal B fields tells us many things, none of which are well understood.
  - Inductive response to time-dependent external fields gives resistivity structure, which can be related to composition and temperature.

Precision Tracking for Rotational Dynamics

- **Variations in rotation vector magnitude (i.e., LOD variation)**
  - Dynamic processes near the surface, such as zonal winds, mass redistribution among atmosphere, polar caps and regolith
  - Whole-body dissipation
- **Variations in rotation vector direction (e.g., precession, nutation, wobble (free nutation))**
  - Radial density distribution (e.g., total moment of inertia, core moment of inertia)
  - Dissipation in the mantle, core (tidal dissipation, fluid core dissipation)
  - Core structure (outer/inner core radii, flattening, momentum transfer)
- **These quantities can be related to the radial density and elasticity (which depends on composition) and damping (which derives from viscosity, related to temperature and composition).**

Planetary Heat Flow

Constrains:

- Thermal and volatile history
- Distribution of radiogenic elements
- Thickness of lithosphere
- Subsurface environment, energy source for chemoautotrophic life forms
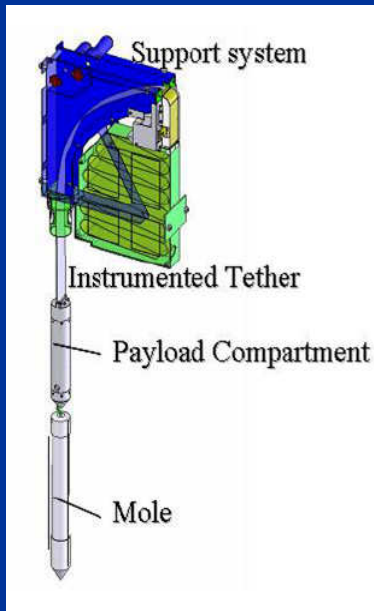
Key challenges:

- Measuring the thermal gradient beneath the annual thermal wave, at 3-5 m depth.
- Accurately measuring the thermal gradient and conductivity in an extremely low conductivity environment where self-heating is an issue.
- Effects of local topography
- Long-term fluctuations of the surface temperature and insolation (climate variations, obliquity changes, etc.)
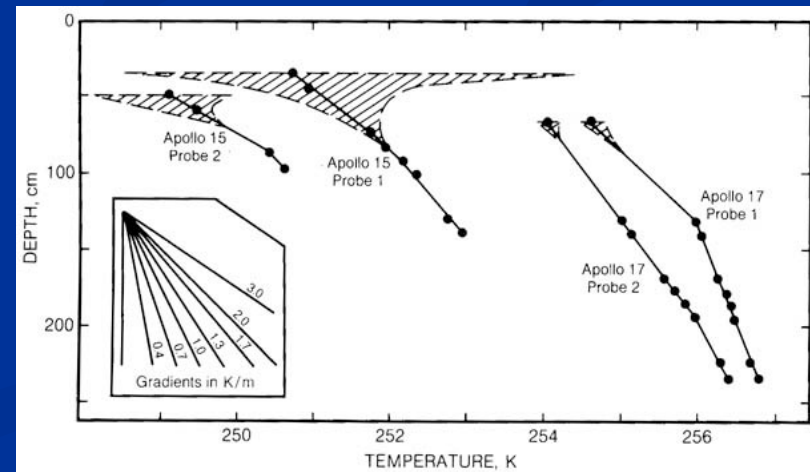
Electromagnetic Sounding

- **Uses ambient EM energy to penetrate the crust and upper mantle.**
- **Is widely used in terrestrial resource exploration and studies of the lithosphere and the deep mantle.**
  - Related methods used to detect subsurface oceans in Galilean satellites and to sound interior of the Moon.
- **Two measurement methods:**
  - Magnetotellurics (10^{-2}-10^2 Hz). Form frequency-dependent EM impedance from orthogonal horizontal electric and magnetic fields
  - Geomagnetic Depth Sounding (10^{-5}-1 Hz). Form EM impedance from 3-component magnetic fields at 3 surface stations.
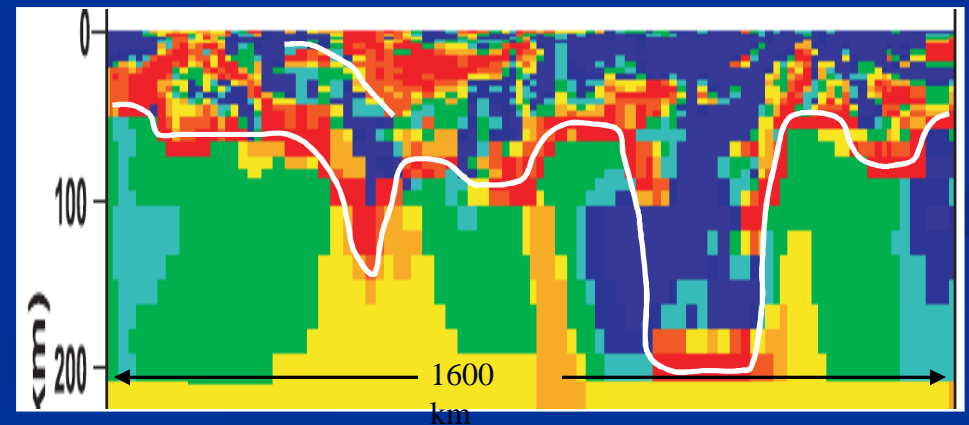
EM sounding can help determine:
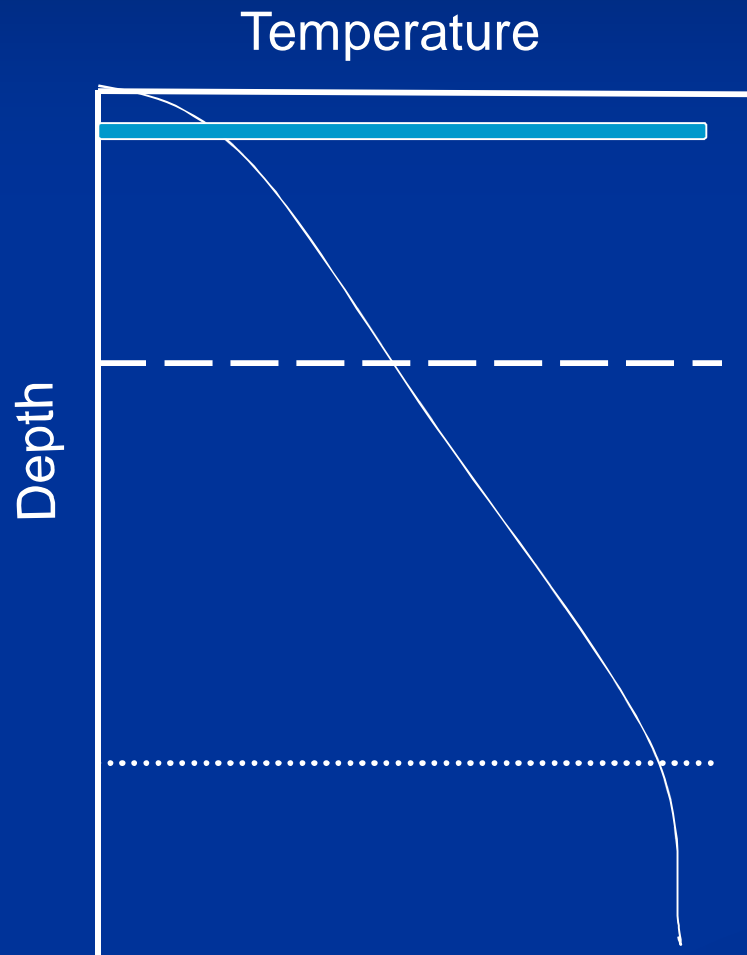Crustal thickness
Depth to ground water
Temperature profile in mantle lithosphere
Low frequency EM environment

Synergies Among Instruments

Temperature

Depth

Temperature and Water in the Crust

< Liquid water: EM sounding, & seismic attenuation; T constrained to ±10°C if water is detected

< Crustal thickness defined by seismology

Heat flow determines thermal gradient and helps constrain distribution of radiogenic elements between crust and mantle

< Thermal lithosphere detected by seismology and EM sounding

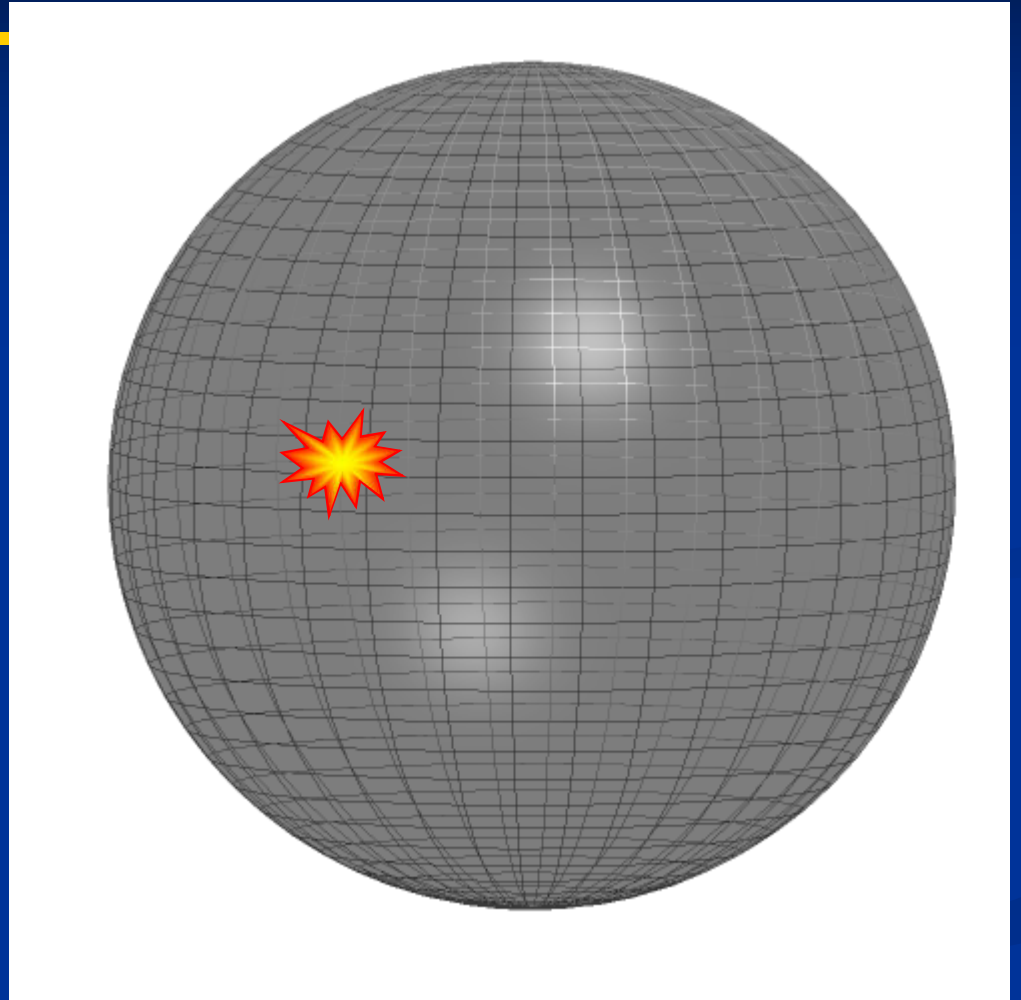< Upper mantle T constrained by petrology and seismic velocity

How Many Stations for How Long?

Q: How many seismologists does it take to screw in a light bulb?

A: Only one. But it takes four to find the bulb.

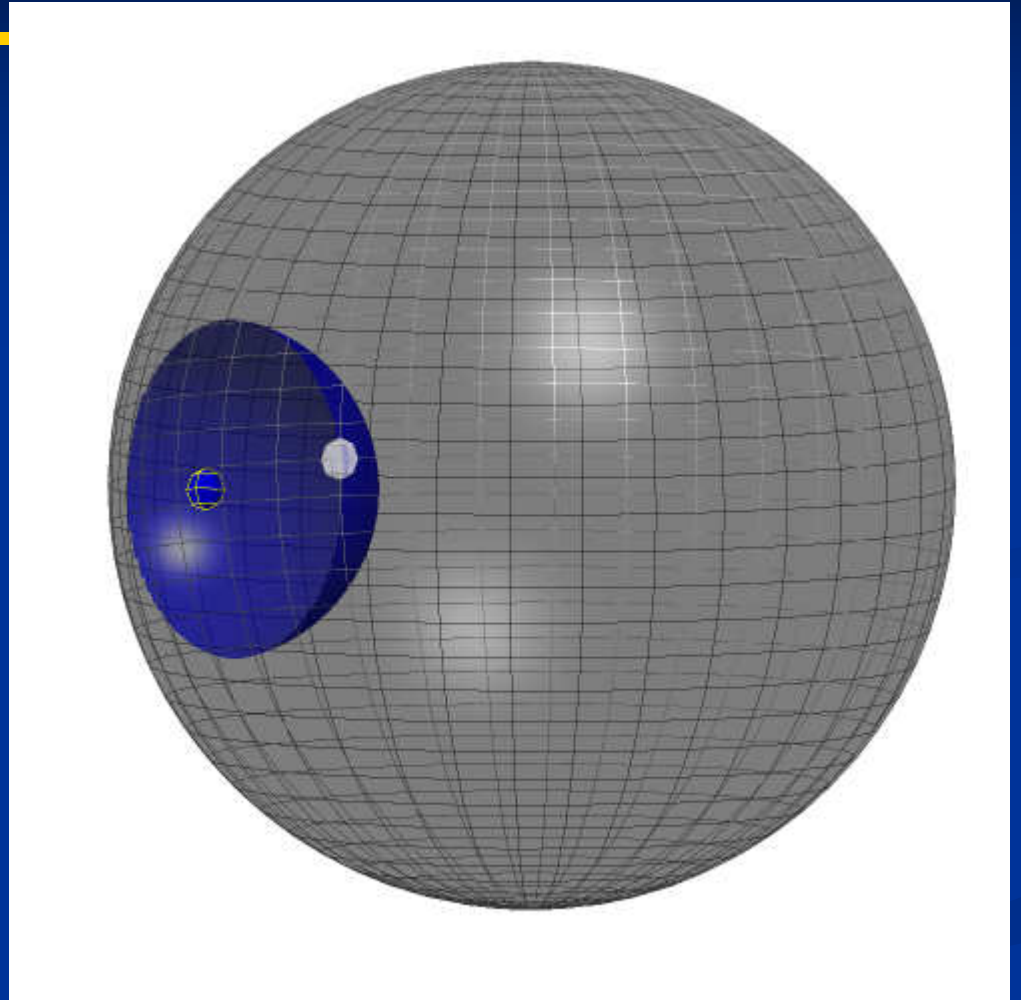# Locating a Marsquake

Assume a quake on a homogeneous planet…

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1 Station:

P and S arrivals allow restricting the location to the surface of a sphere.

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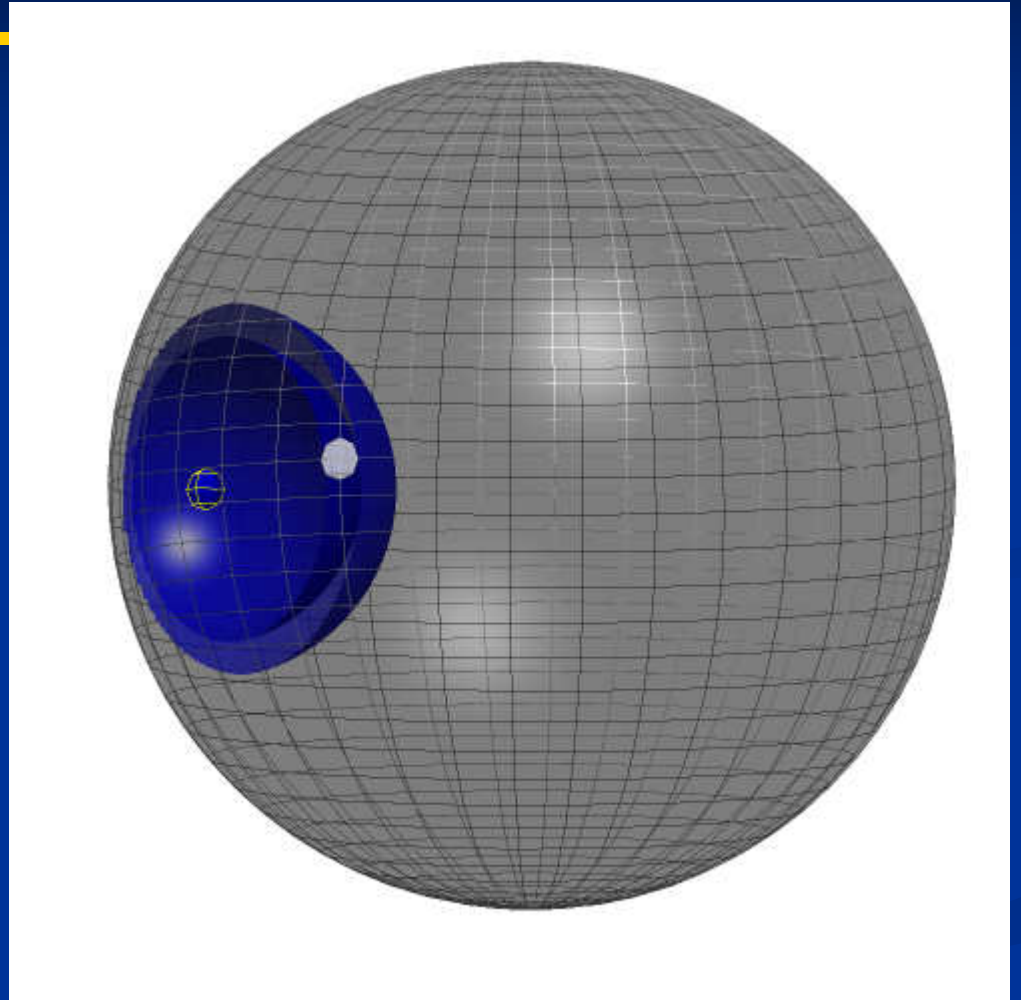Since observations are always inaccurate, the surface becomes a shell of finite thickness.
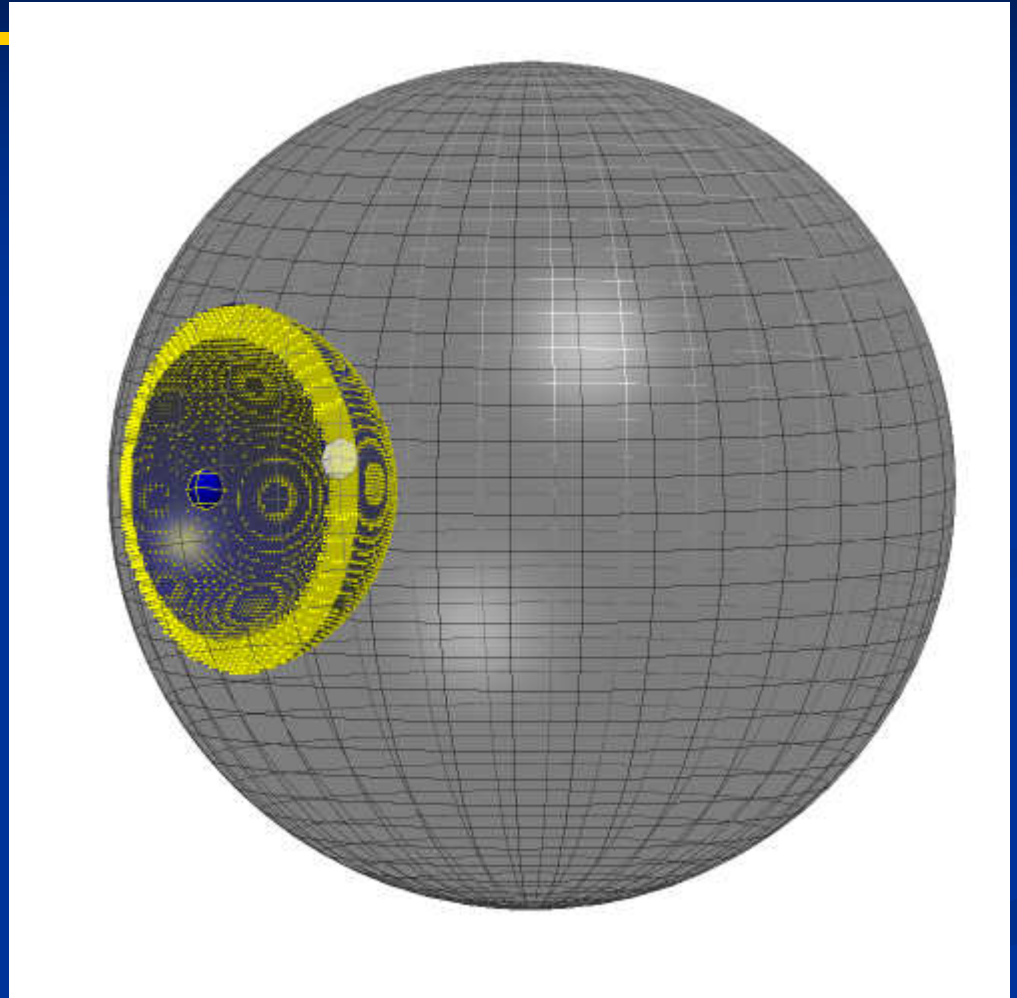
Locating a Marsquake

Assume a quake on a homogeneous planet…

1 Station:

P and S arrivals allow restricting the location to the surface of a sphere.

Since observations are always inaccurate, the surface becomes a shell of finite thickness.

All points within this shell (**yellow**) are candidate locations and cannot be distinguished any further without more data.
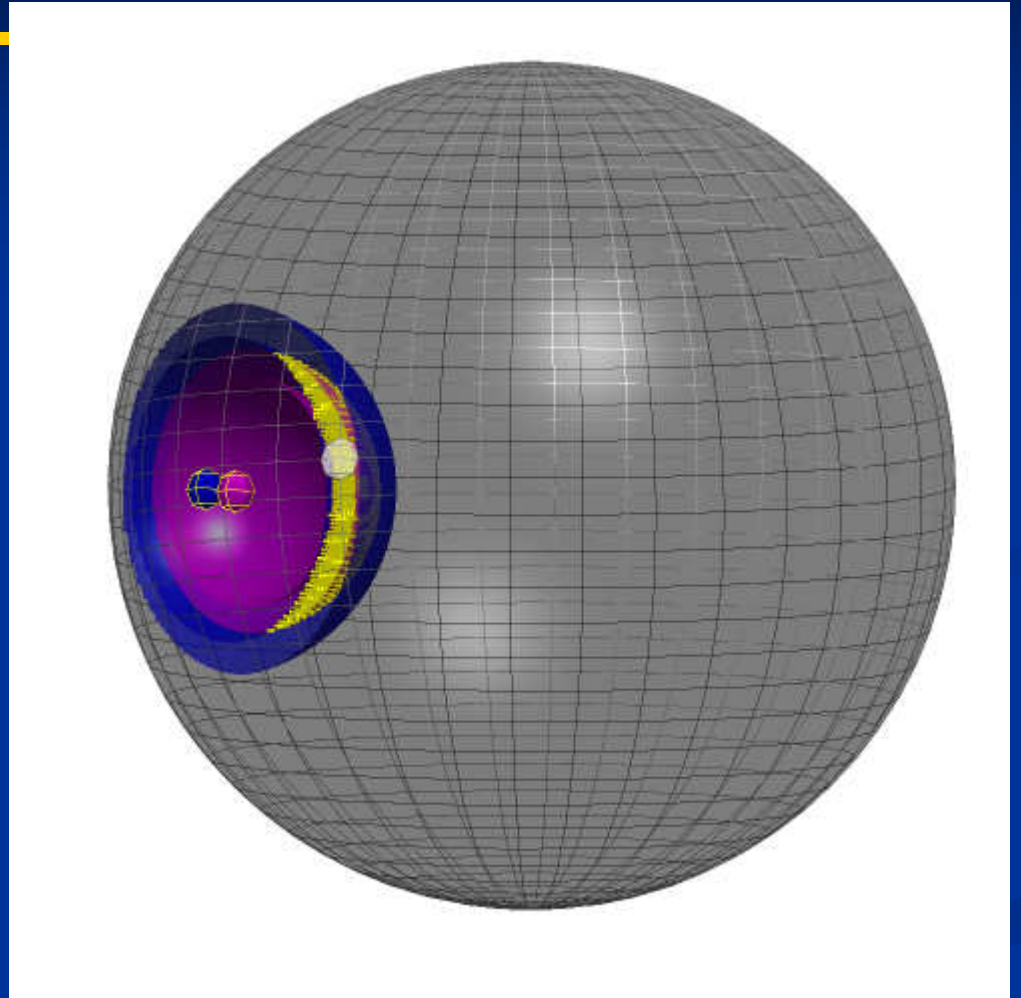
Locating a Marsquake

Assume a quake on a homogeneous planet…

2 Stations:

P and S arrivals of both stations define two shells. All points on their intersection (yellow) are candidate locations.
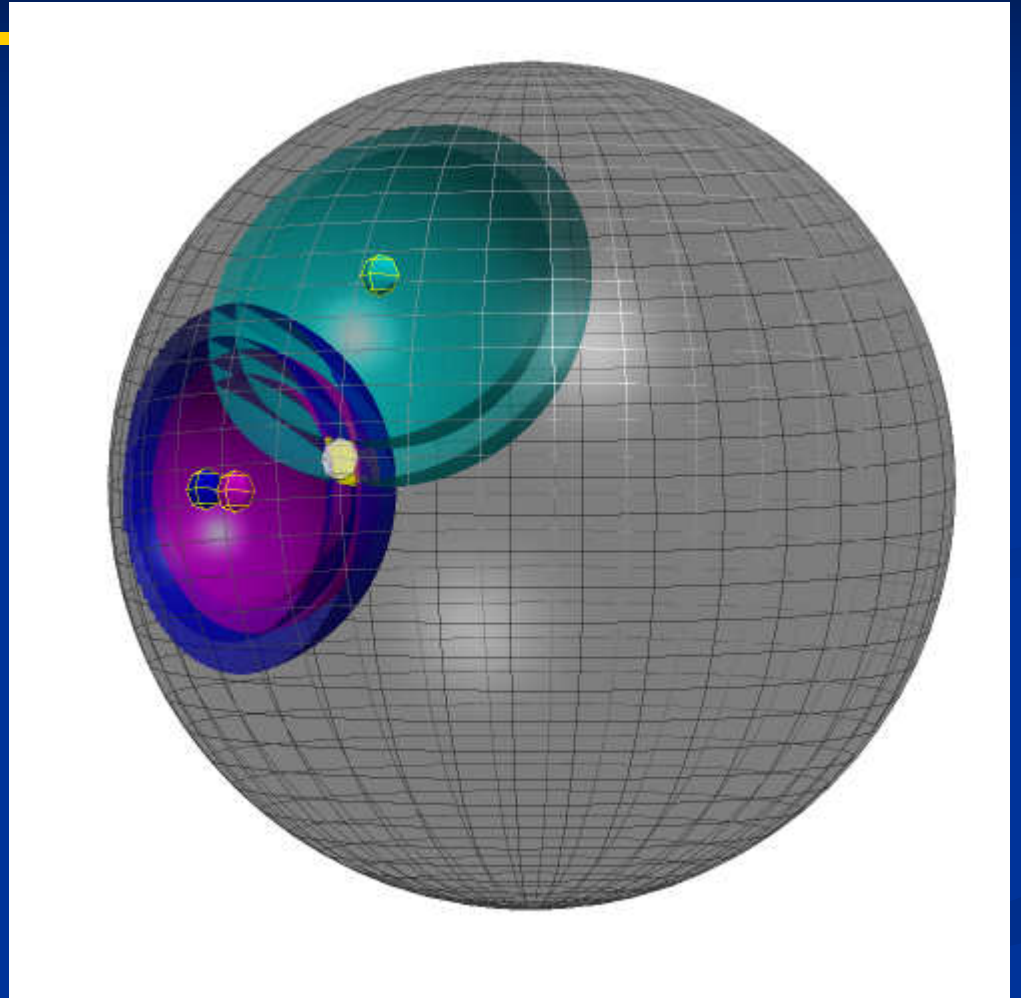
Locating a Marsquake

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3 Stations:

P and S arrivals of all stations define three shells. All points in their intersection are candidate locations.
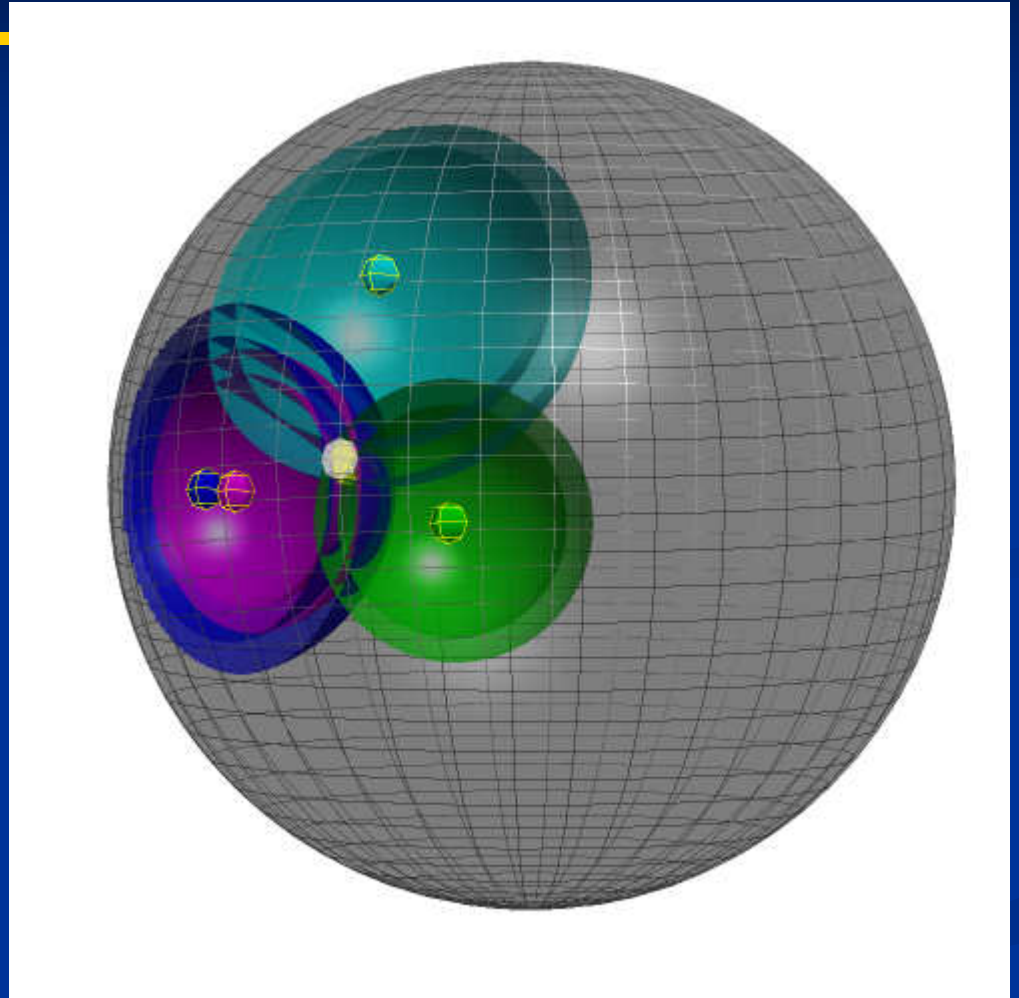
Locating a Marsquake

Assume a quake on a homogeneous planet…

4 Stations:

Four stations are needed to actually determine the velocity structure within the planet, instead of only assuming it.

Number of Stations for Seismology

- **Four stations are required to formally obtain the interior velocity using body wave arrival times.**

- With a non-uniform velocity it is possible to derive a velocity profile whose uncertainty decreases with larger number of events.

- There are a number of techniques for using single-station data to obtain interior structure information.

Surface Wave Seismology
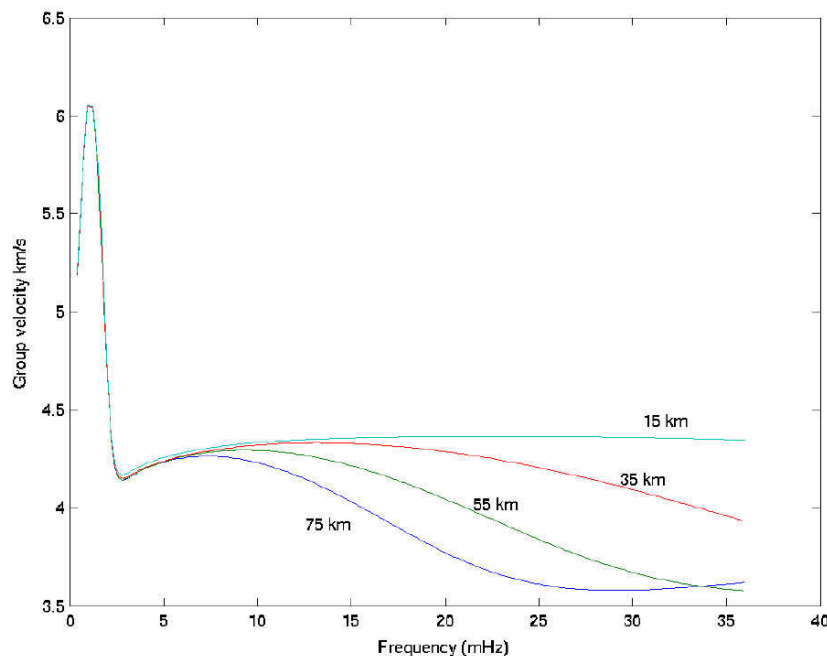
Simulated surface wave dispersions curves for different crustal thicknesses on Mars.

- ■ **Surface waves "feel" to different depths depending on their wavelength.**
 - ■ Longer wavelengths induce particle motion (and are thus affected by the material properties) at greater depths.
- ■ **Therefore surface waves are dispersive, i.e., their velocity changes with frequency.**
- ■ **The "dispersion curve" $v(f)$ has information about the shallow (few 100 km) structure.**
- ■ **Thus, we can get some internal structure information from a single seismic station (using the arrivals of the R1 and R2 phases).**
- ■ **Alas, only relatively large quakes (e.g., M > 5) tend to generate surface waves on Earth.**

Normal Mode Seismology

Earth
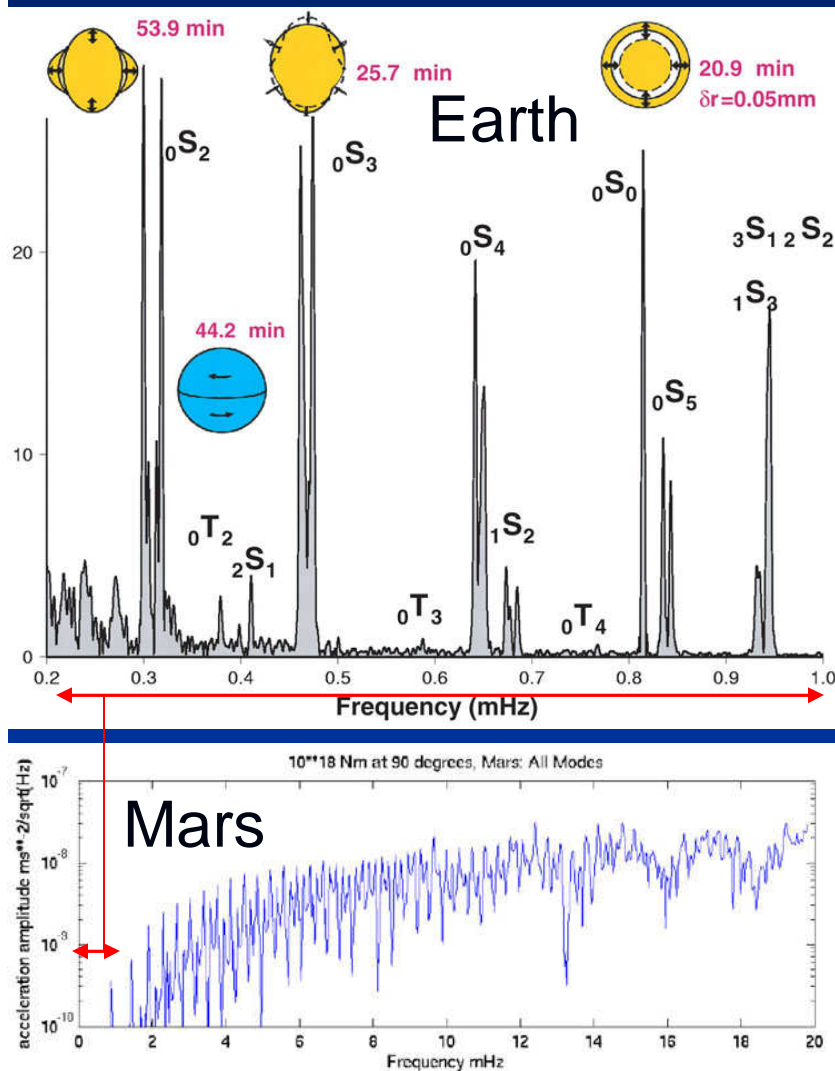
Mars

- Normal modes (sometimes called "free oscillations") are the ringing overtones (eigenmodes) of a planet.

- For any model for Mars' elastic and density structure, the discrete frequencies (eigenfrequencies) can be calculated.

- These can be compared with the observed peaks in the low-frequency spectrum of a marsquake.

- **Again, only one station would be necessary for interior structure determination.**

- Alas and alack, only REALLY large quakes on the Earth (M > 7) generate normal modes at long periods; normal modes are expected to be detectable only for f>5 mHz for 5.5 on Mars

Tidal Response

- **The displacement of the solid surface and equipotential surface induced by an external tidal potential depends on the radial structure of the planet:**
    - Radial density distribution, which depends on composition
    - Dissipation in the mantle and core, which derives from viscosity (related to temperature and state, i.e., fluid vs. solid) and composition
- **Calculated solid-body tidal responses at the surface:**
    - Sun (24.6 hr) ~30 mm (swamped by diurnal thermal noise)
    - Phobos (7.7 hr) ~10 mm
    - Deimos (30.3 hr) < 1 mm (below detection level)
- **Distinguishing the effect of a fluid core on the Phobos tide is within the capabilities of a VBB seismometer with ~6 months of recording – no seismic events necessary.**

Other Single-Station Seismic Techniques

- **Impact Events**
  - If location of impact can be determined from orbital imaging, location parameters are removed from the solution, leaving only v and t as unknowns.
- **First Motion (FM) Analysis**
  - Because first arrival is a P wave, the FM measured from the 3-axis seismograms gives the vector direction of the emerging ray.
  - Can get direction to source from the FM azimuth
  - Can get distance to source from the FM emergence angle (requires velocity model)
- **P – S**
  - Time interval between P and S arrival can be used to derive distance and event time (requires velocity model)
- **Noise Analysis**
  - Analyze accumulated background noise at a station
  - Can derive crust and upper mantle structure and regional layering from phase velocity analysis
- **Receiver Function Analysis**
  - Can use P-S phase conversion of teleseismic signals at the crust/mantle boundary to derive crustal structure from correlation of vertical and horizontal components

How Many Stations for Seismology?

- **One station** may provide important constraints on interior structure.
    - Given our nearly complete ignorance of the interior, even a modest amount of information will be valuable.
    - However, interpretation will depend on models and assumptions to an uncomfortable degree.
    - Detection will be biased toward a single region of the planet.
    - Application of the single-station techniques described previously can be problematic in a new environment.
    - Perhaps its greatest value would be as a "pathfinder" for a full network, indicating location and level of seismicity, and character of seismic signals and noise in this unexplored environment.

- **Two stations** represent a major increase in value.
    - Allows the unambiguous recognition of seismic signals through correlation of arrivals.
    - Significantly decreases the ambiguity of event locations.

How Many Stations for Seismology?

- **Three stations** provide an incremental added value.
  - With relatively few assumptions, can determine quake locations and begin to delineate velocity structure of the mantle.
  - Significantly decreases the geographic detection bias.

- **Four stations are the minimum required to "fully" address the seismology objectives for interior structure.**
  - Allows for the robust inversion on travel times for interior structure without a priori assumptions.
 - Provides reasonably complete global coverage.

How Many Stations for Precision Tracking?

- A single station can provide some valuable basic measurements.
  - It would allow the extension of the precession measurement baseline began by Viking and Pathfinder, improving the moment of inertia determination by a factor of ~10.
  - Precession, nutations, LOD variations, and polar motion can all be detected by a single station; however, their signatures are difficult to separate with a single tracking geometry.
- Additional stations, with a spread in both latitude and longitude provide the ability to deconvolve the various contributions to rotational variation.
  - Tracking through an orbiter may also provide additional geometries, albeit with lower precision.

How Many Stations for Heat Flow?

- The key issue for heat flow is the intrinsic variability of the planet: how representative of the global heat flow is a single measurement?
    - Local variability
    - Regional variability (on the Earth there is a factor of two difference between continental and oceanic crust).
- Whereas a single measurement would be valuable (especially since it could be added to later), a minimum of four measurements in key regions are required to produce a strong global estimate.
    - Northern Plains
    - Southern Highlands
    - Tharsis
    - A repeat of at least one of the above.
- EM sounding, which is concerned with the structure of the crust and upper mantle, follows essentially the same logic.

Science vs. Number of Stations
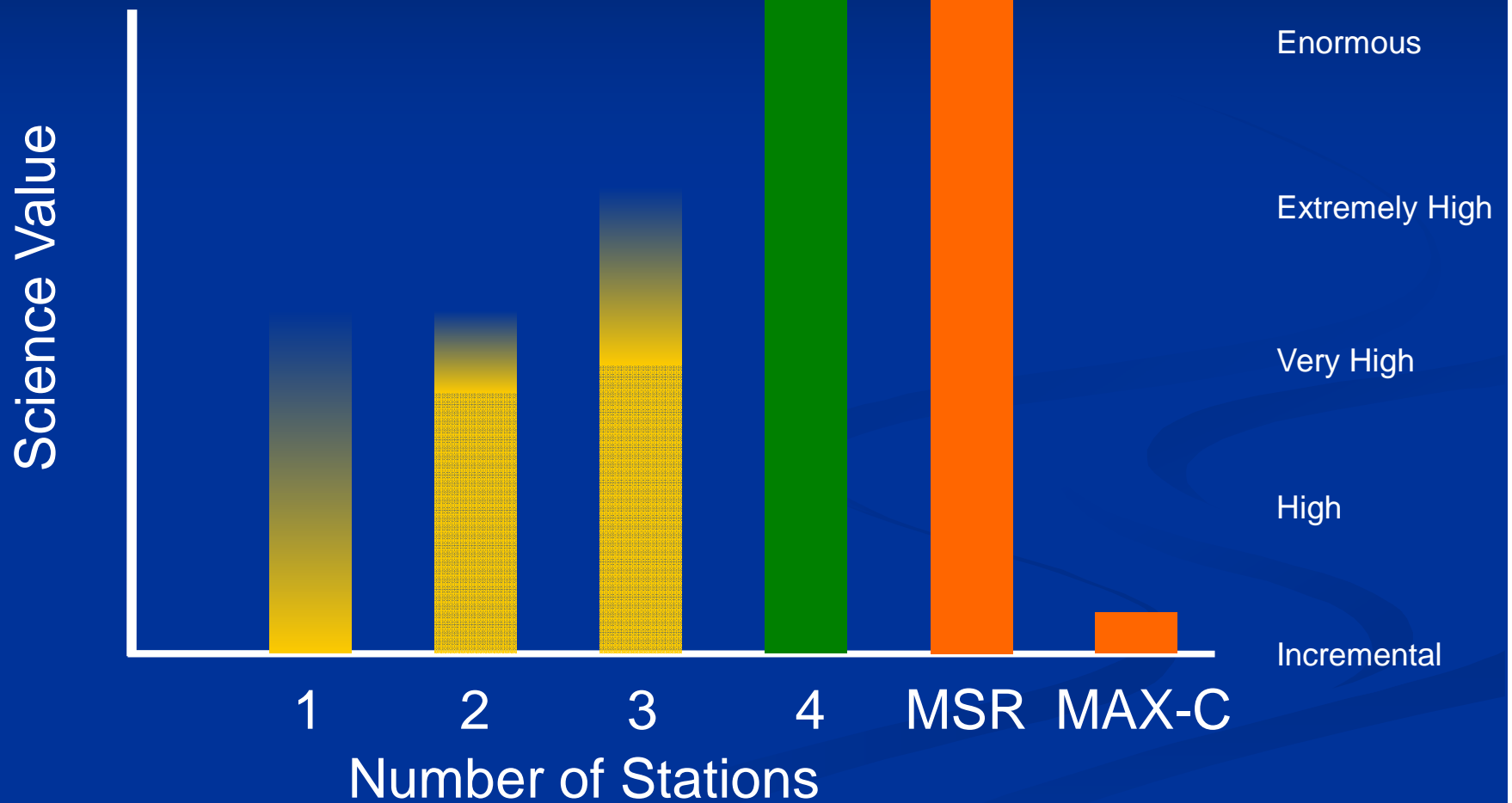
How Long Must the Network Last?

- For seismology, several lines of analysis of expect seismicity rates indicate that in order to get sufficient number of events for analysis, a minimum of one half Mars year is needed. The uncertainty in these projections drive a requirement of a full Mars year.

- Although the long-term precession can be determined after ~6-12 months, solar forcing of the rotation drives a tracking requirement of a full Mars year in order to measure the higher-order rotational variations.

- Heat flow measurements require a significant portion of the seasonal cycle to observe and remove the annual thermal wave contribution to the thermal gradient.

- **Thus, we derive a strong requirement for a full Mars year of operation for the complete network.**

Conclusions

- **Planetary interior investigations feature prominently all 2003 Decadal Survey Themes, and are key to understanding Solar system history and processes.**

- **Seismology (first and foremost), Precision Tracking, Heat Flow and Electromagnetic Sounding are the key measurements for subsurface geophysical network science**

- **Four stations, simultaneously operating for a full Mars year, are the minimum required to fully address all objectives for understanding Mars' interior structure.**

Backup Material

NetSAG Membership

- Bruce Banerdt (Co-Chair, JPL/Caltech)
- Tilman Spohn (Co-Chair, DLR)
- Uli Christensen (MPI)
- Veronique Dehant (ROB)
- Lindy Elkins-Tanton (MIT)
- Bob Grimm (SwRI)
- Bob Haberle (NASA-Ames)
- Martin Knapmeyer (DLR)
- Philippe Lognonné (IPGP)

- Franck Montmessin (LATMOS)
- Yosio Nakamura (ret.)
- Roger Phillips (SwRI)
- Scot Rafkin (SwRI)
- Peter Read (Oxford)
- Jerry Schubert (UCLA)
- Sue Smrekar (JPL/Caltech)
- Deborah Bass (Mars Program, JPL/Caltech)

DS Theme 1: The Past

- **What led to the unique character of our home planet?**
  - Bulk compositions of the inner planets
    - Determine interior (mantle) compositions
  - Internal structure and evolution
    - Determine the horizontal and vertical variations in internal structure
    - Determine the compositional variations and evolution of crusts and mantles
    - Determine major heat-loss mechanisms
    - Determine major characteristics of iron-rich metallic cores
  - History and role of early impacts
  - History of water and other volatiles

  Gold $\Rightarrow$ significantly addressed by network mission

DS Theme 2: The Present

- **What common dynamic processes shape Earth-like planets?**
  - Processes that stabilize climate
    - Determine the general circulation and dynamics of atmospheres
    - Determine processes and rates of surface/atmosphere interaction
  - Active internal processes that shape atmospheres and surfaces
    - Characterize current volcanic and/or tectonic activity
  - Active external processes that shape atmospheres and surfaces

DS Theme 3: The Future

- **What fate awaits Earth's environment and those of the other terrestrial planets?**
  - Vulnerability of Earth's environment
  - Varied geological histories that enable predictions of volcanic and tectonic activity
    - Determine the current interior configurations and the evolution of volcanism and tectonism
  - Consequences of impacting particles and large objects
    - Determine the recent cratering history and current flux of impactors
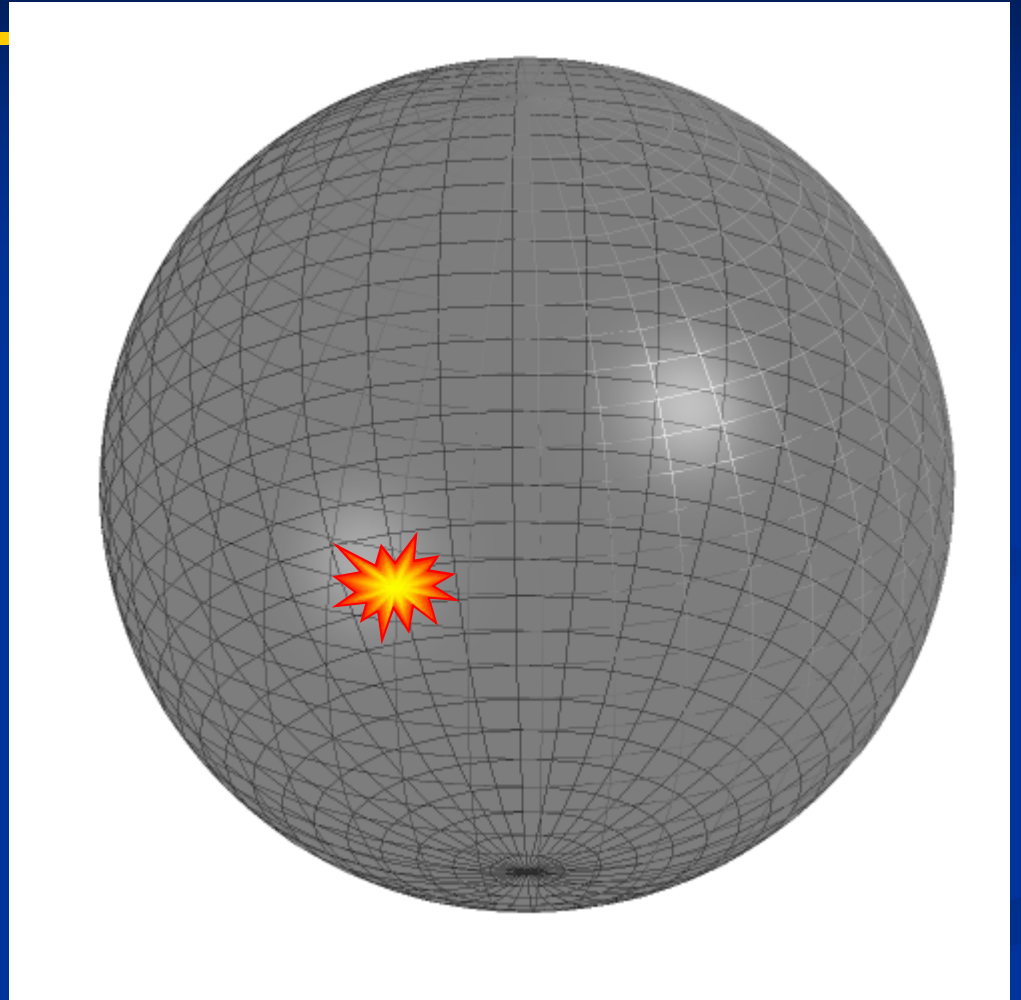 - Resources of the inner solar system

Assume a homogeneous planet:

Propagation velocity of elastic waves is constant.
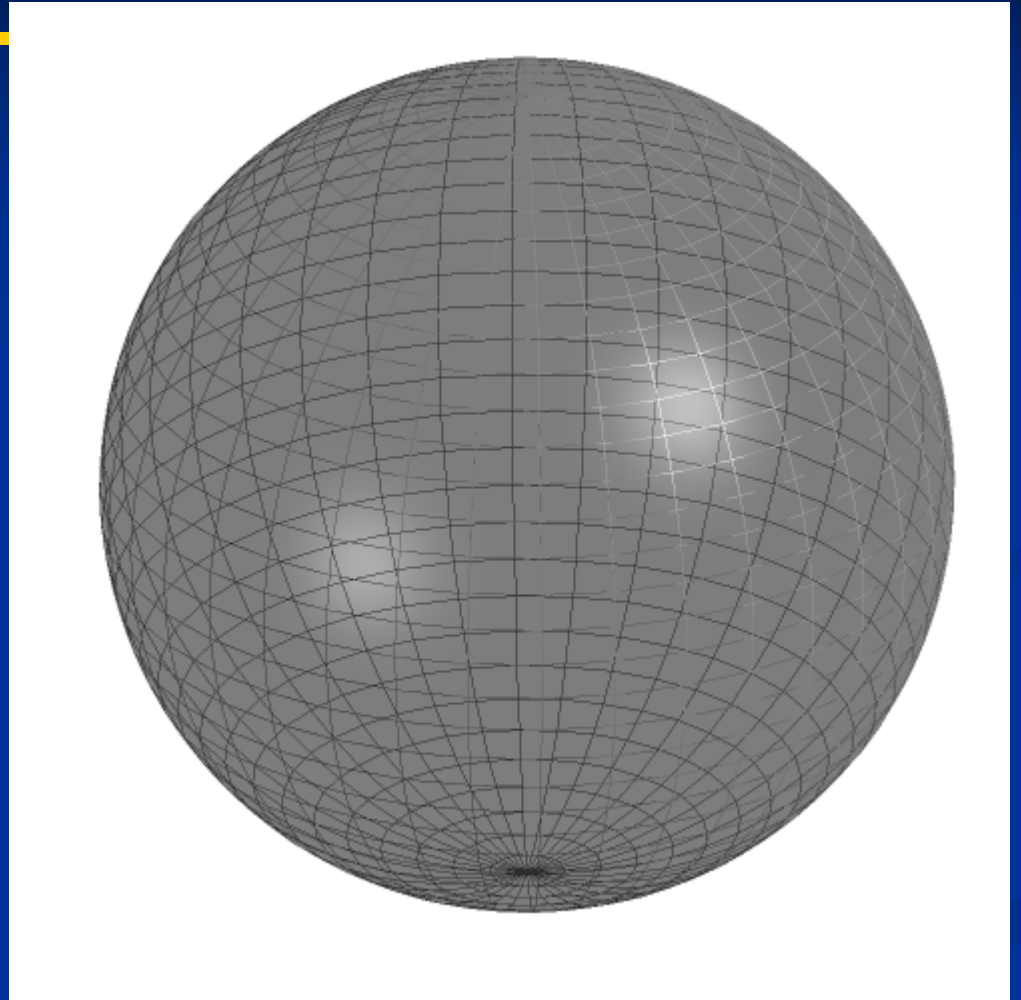
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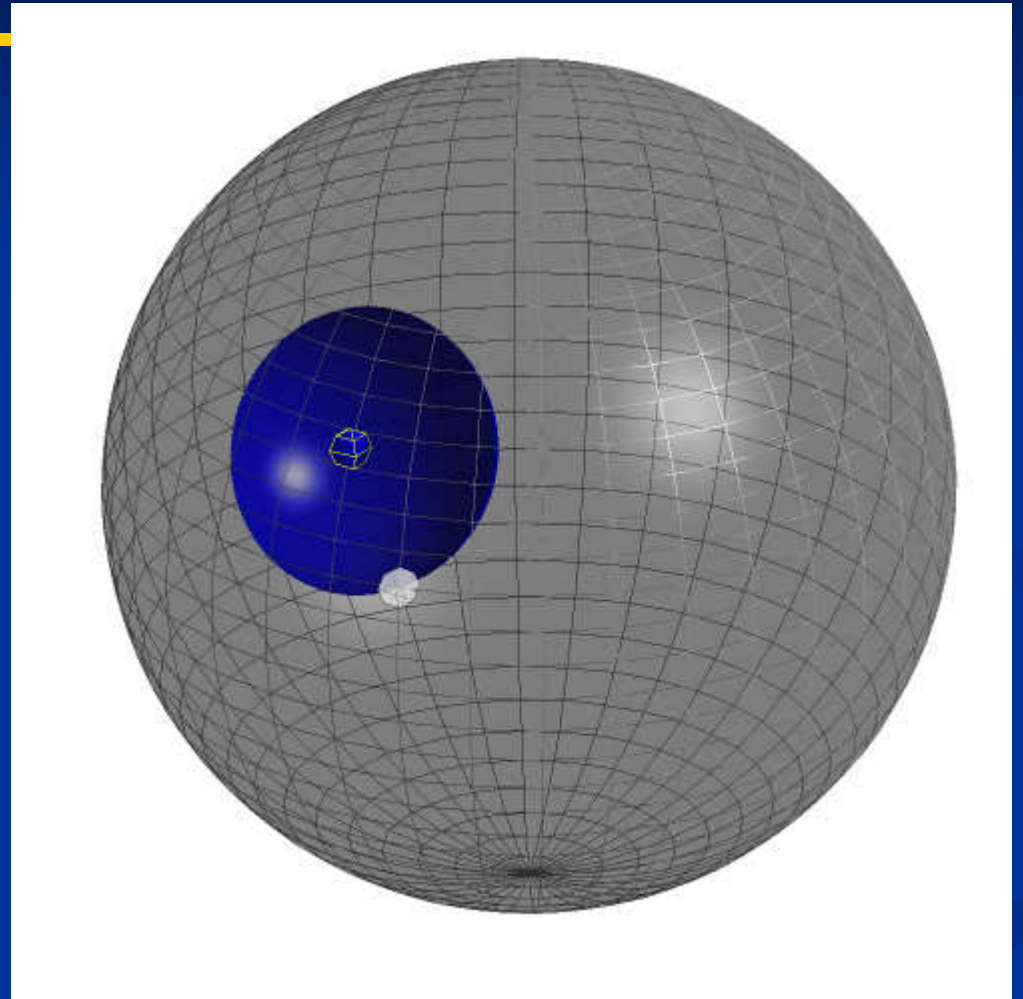
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Let a quake happen.

1 Station:
P and S arrivals allow restricting the location to the surface of a sphere. Since observations are always inaccurate, the surface becomes a shell of finite thickness. (here: ±10% of distance for illustration purpose)

All points within this shell (**yellow**) are candidate locations and cannot be distinguished any further without more data.

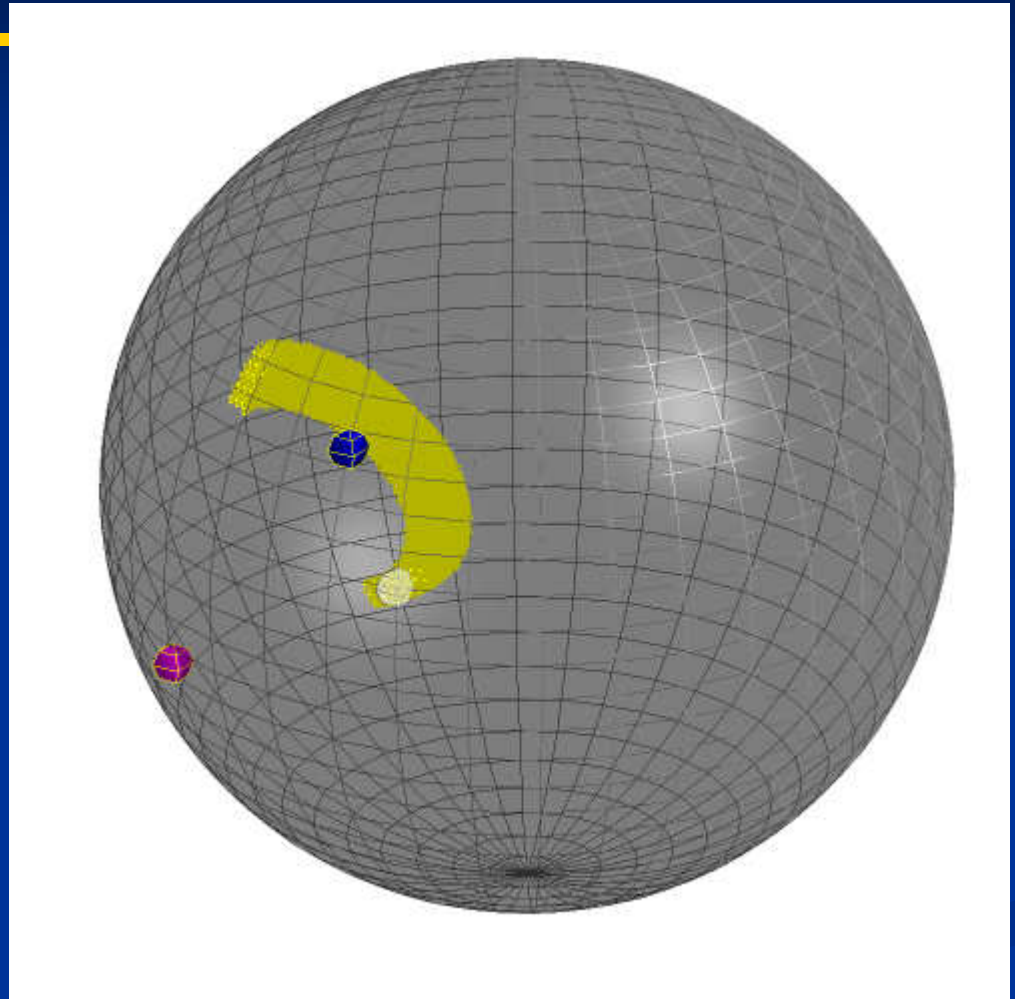Decadal Survey Mars Panel – Caltech, Pasadena, CA
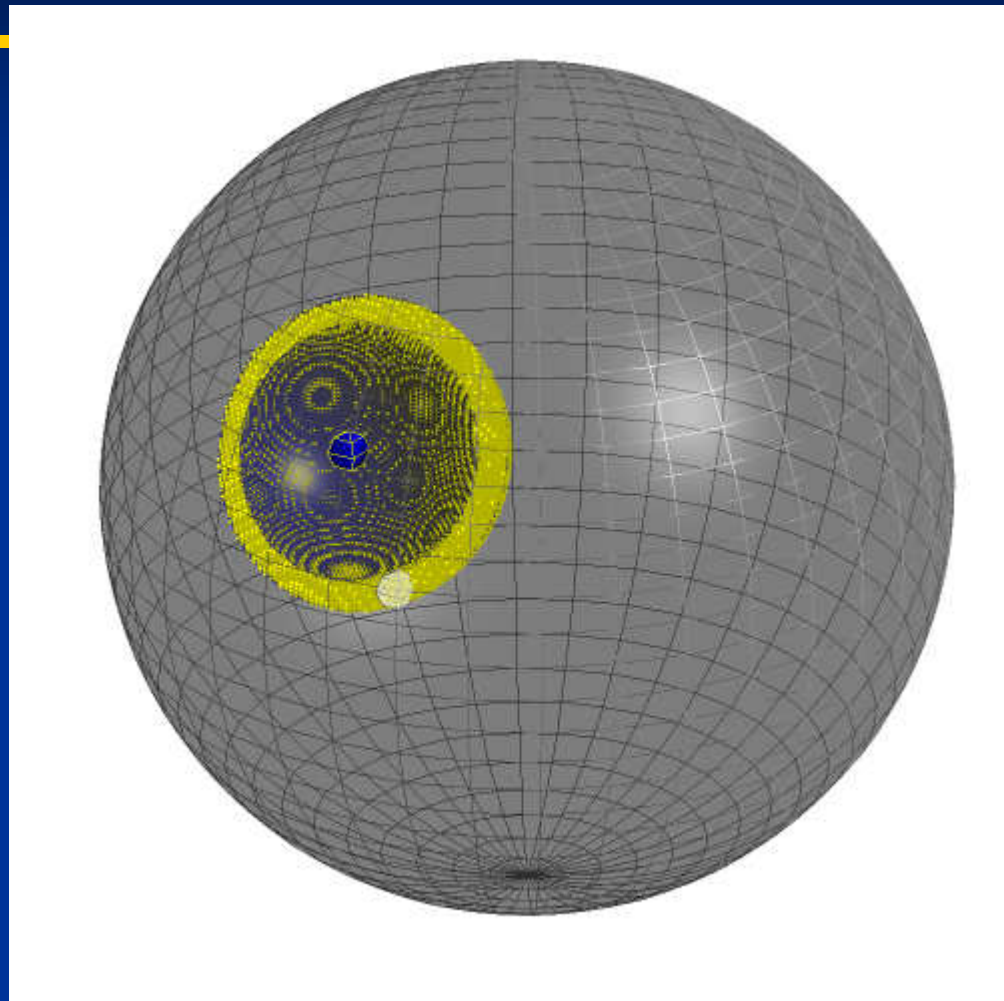
Assume a homogeneous planet:

Let a quake happen.

2 Stations:
P and S arrivals of both stations define two shells. All points in their intersection are candidate locations.
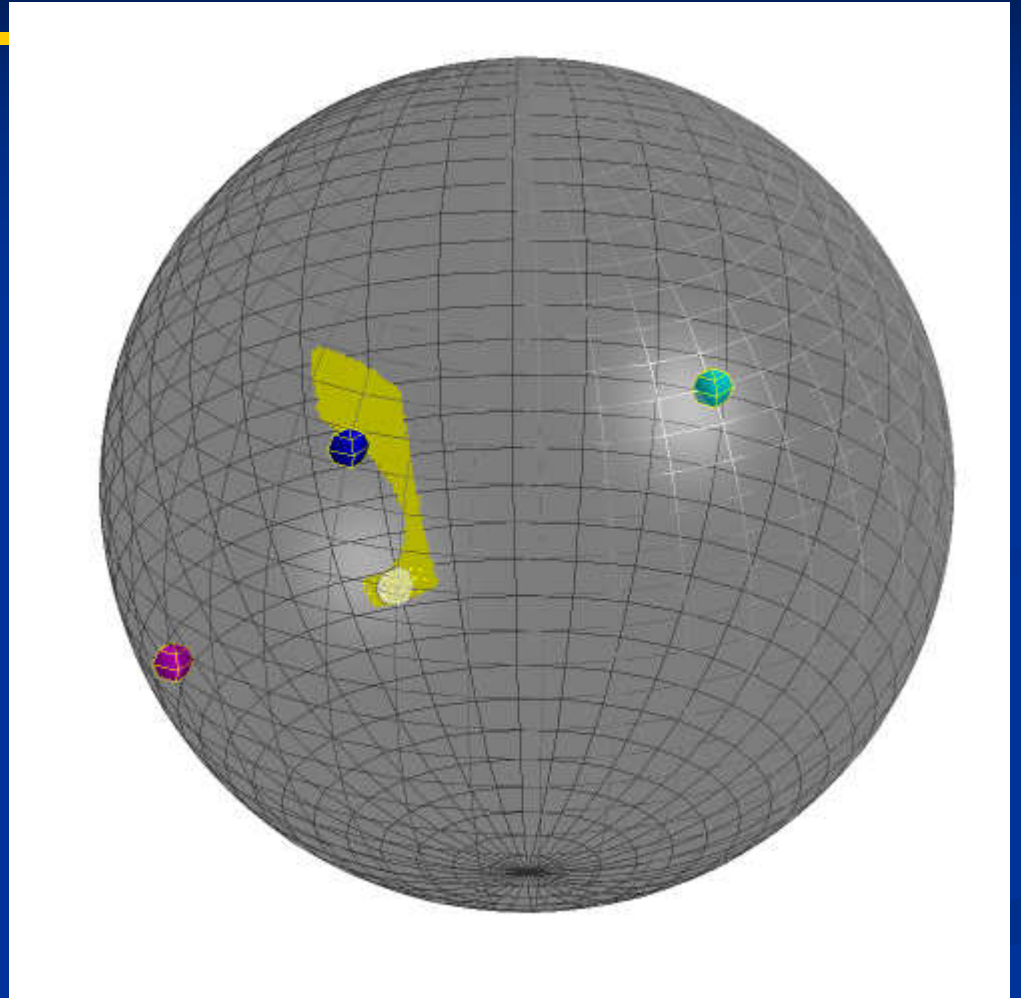
Assume a homogeneous planet:

Let a quake happen.

3 Stations:
P and S arrivals of all stations define three shells. All points in their intersection are candidate locations.

Assume a homogeneous planet:

Let a quake happen.

4 Stations:

In the nominal NetLander network, the 4th station hardly contributes to the location but is used to constrain the core structure.

In a real Planet, it would be within the P and S wave shadows of the