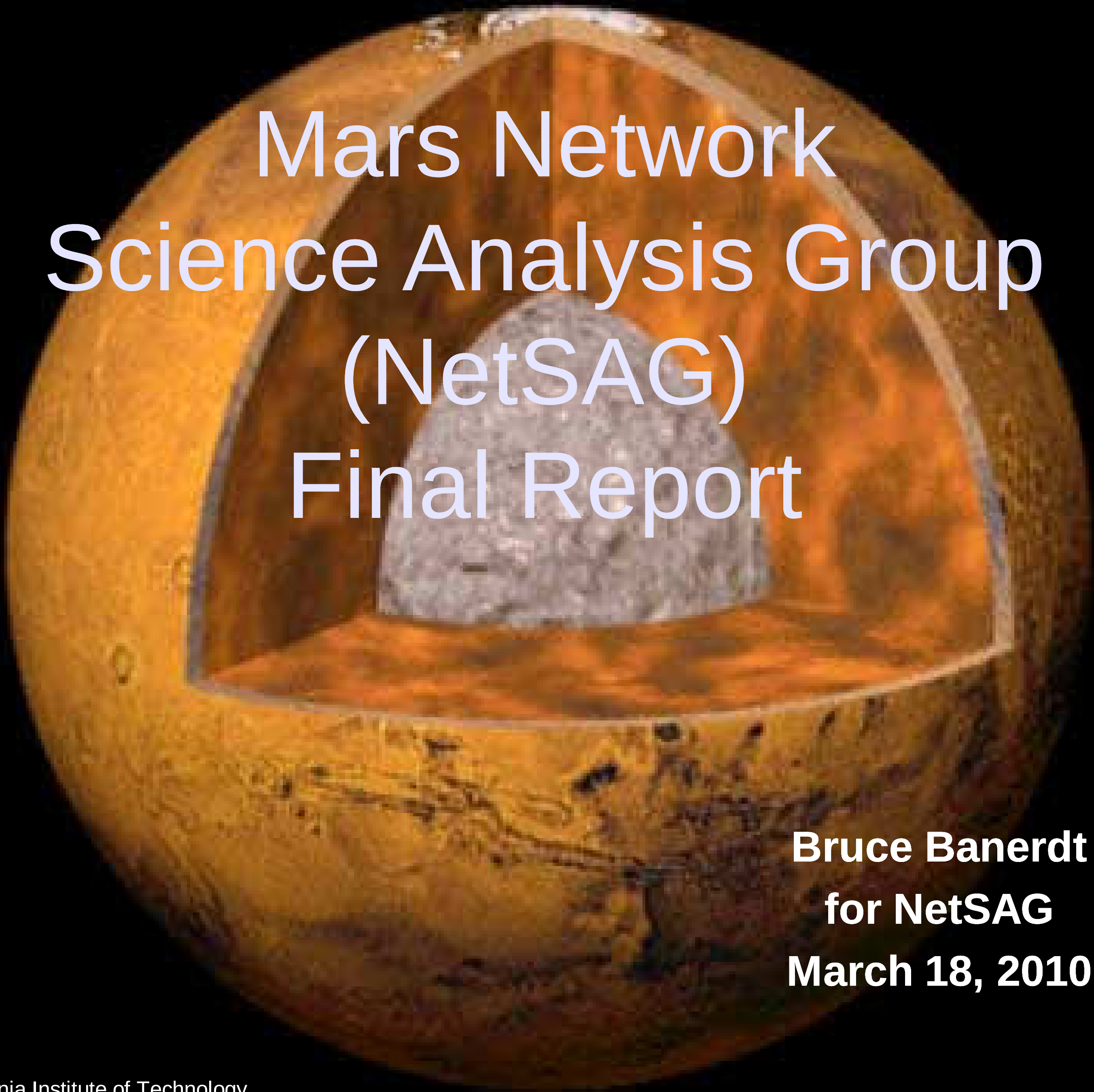


Mars Network Science Analysis Group (NetSAG) Final Report

Bruce Banerdt
for NetSAG
March 18, 2010

Summary

- NetSAG has completed its work and has addressed all charter tasks.
- A set of compelling, achievable science objectives were identified and articulated, which relate directly to MEPAG Goals and Objectives.
- Mission requirements in terms of number of stations, lifetime, and instrument performance were developed.
- In particular, NetSAG investigated the trade between number of stations and science objectives, and produced recommendations regarding network composition.
- Charter tasks regarding mission implementation needs and technology requirement were addressed.

Membership

- 🟨 Bruce Banerdt (Co-Chair, JPL)
- 🟪 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)
- 🟨 Deborah Bass (Mars Program, JPL)

- 🟨 U.S. member
- 🟪 International member

Charter Tasks

1. Prepare prioritized list of science objectives, and determine thresholds for major advances in understanding Mars with respect to:
    a) Number of nodes
    b) Investigation strategies
    c) Lifetime
2. Assuming that the priority is on interior science, evaluate:
    a) Options and priorities for atmospheric science
    b) Options for surface and subsurface geology
    c) Other science that can take advantage of multiple nodes
3. Document relationships of 1. and 2. above to the MEPAG Goals, Objectives and Investigations
4. Evaluate mission implementation needs, such as landing precision, EDL constraints, estimated budget, etc.
5. Identify long-lead technology development needs

Task 1.
Prepare a prioritized list of science objectives…

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 Investigations

- 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.

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

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.
  - Chemistry of these volatiles (e.g., CO_2 vs. CH_4) depends on the conditions (e.g., oxidation state) of the interior.
  - 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
- …

Highest Priority Science Goals for Geophysical Network

- 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 detailed radial seismic velocity profile of the planet's interior which carries information about fundamental planetary processes.
- Determine the global planetary heat flow.

Task 2.

Evaluate options and priorities for atmospheric science, surface and subsurface geology, and other science.

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.

Tasks 3, 4, 5.

Document relationship to MEPAG Goals, evaluate mission implementation needs, identify technology needs

MEPAG Linkages

- The mapping of the network mission objectives to MEPAG Goals, Objectives, and Investigations is straightforward.
  - Closest linkage is to Objective III.B (Structure, composition, dynamics, and evolution of Mars' interior)
  - But there are important links throughout, including
    - I.A (Past habitability)
    - II.A (Present climate, and climate processes)
    - III.A (Nature and evolution of the geologic processes that have created and modified the Martian crust)

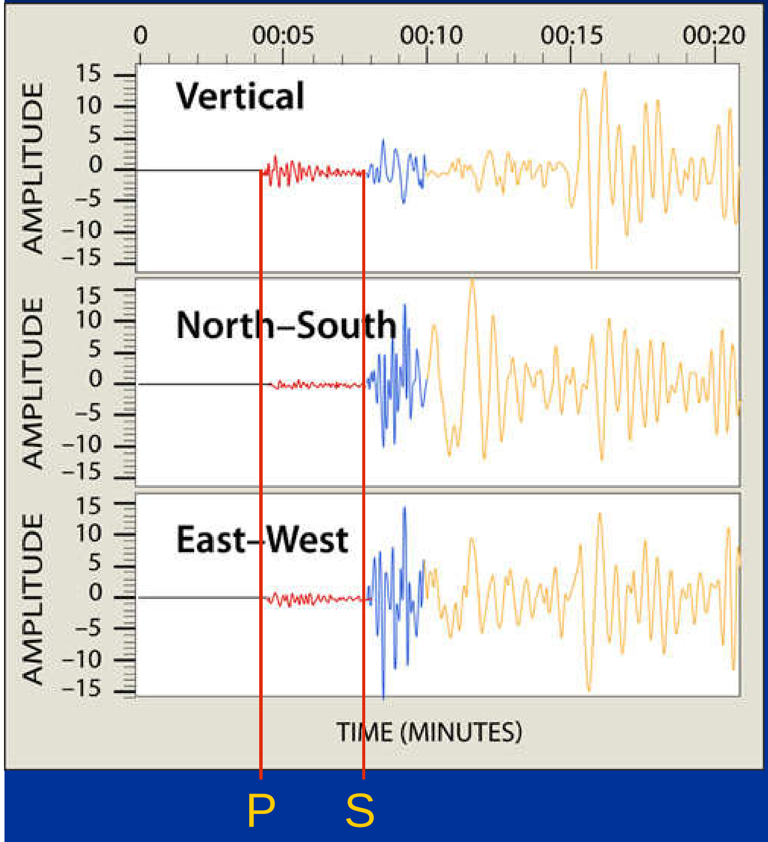
Mission Implementation and Technology

- Network mission implementation has been thoroughly studied previously, and NetSAG has little to add.
- Key mission requirements:
  - Landing (with significant latitudinal distribution)
  - Lifetime
  - Telemetry
  - Dirt access
- Cost is < $1.5B for 4 landers, ~ $0.5B for one.
  - This is being validated by Decadal Survey committee
- No new technology is required.
  - Cheap landing system and/or VBB seismometer with shock tolerance might help.

Task 1a,c.
Number of Nodes, Lifetime

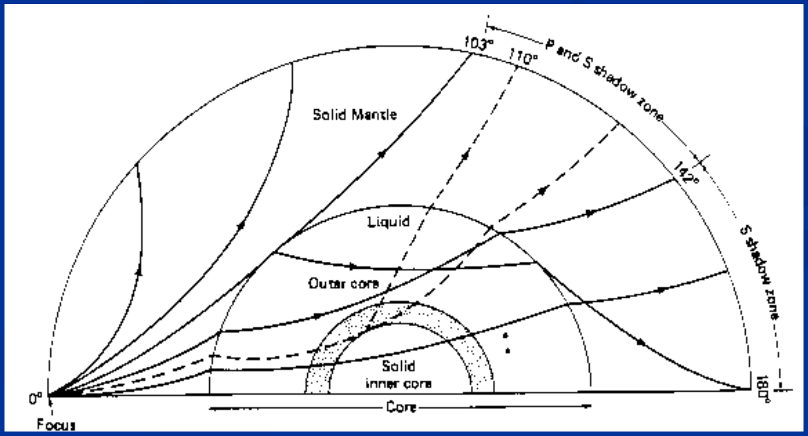
Geophysical Network Measurements

Body Wave Seismology

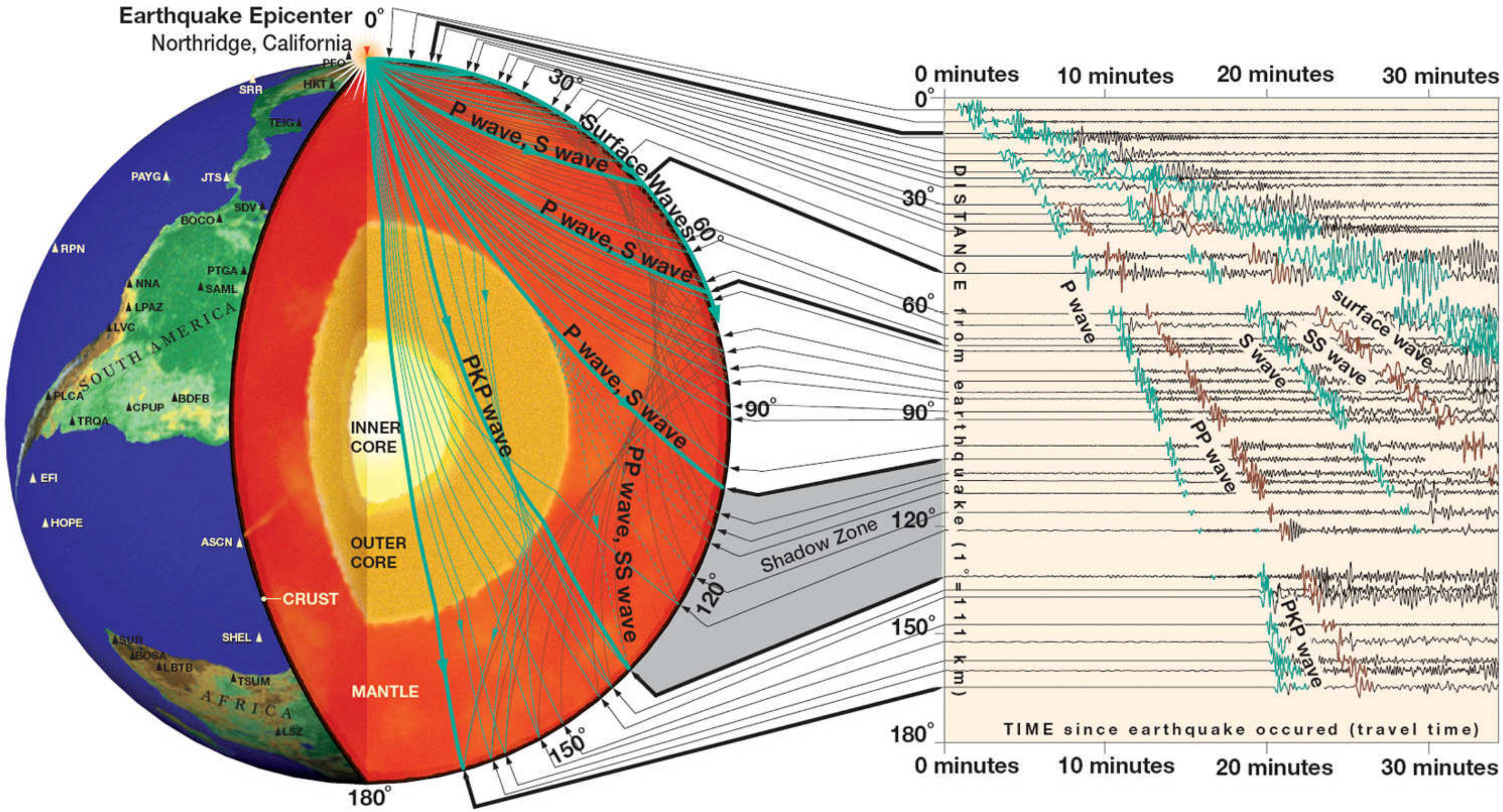


- The most straightforward seismic method is body-wave travel-time analysis.
- Must accumulate events at various distances from the sensor to probe the full range of depths.
- Need lots of events!
- Need to detect each event at 3 or more stations to be able to reliably locate its source

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.

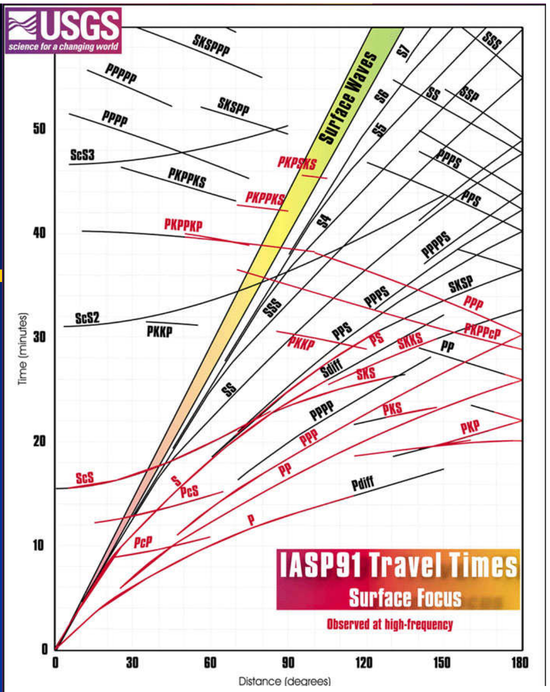


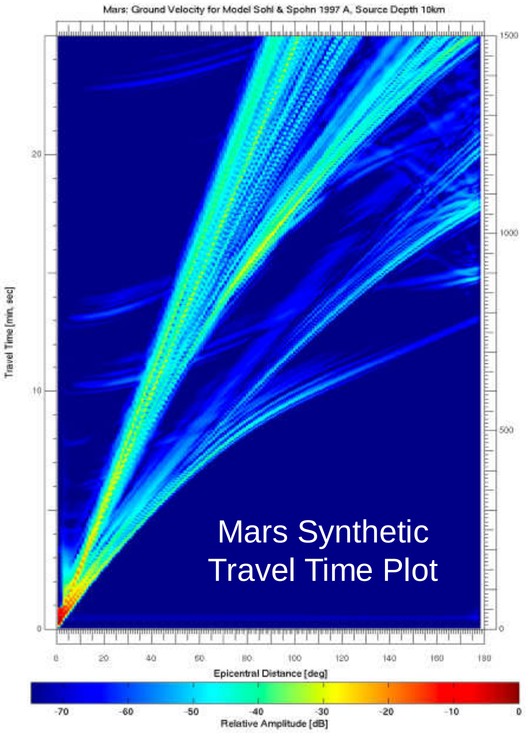
Travel Time Analysis



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

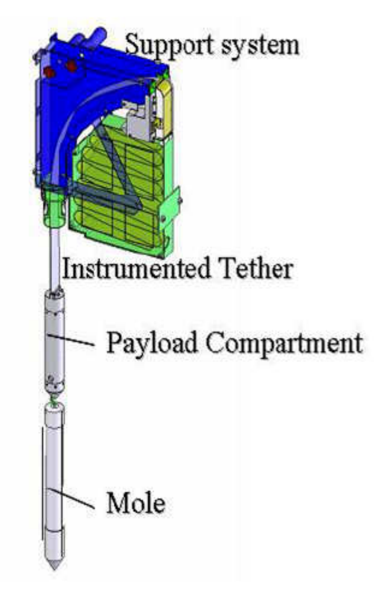
Precision Tracking for Rotational Dynamics

- **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

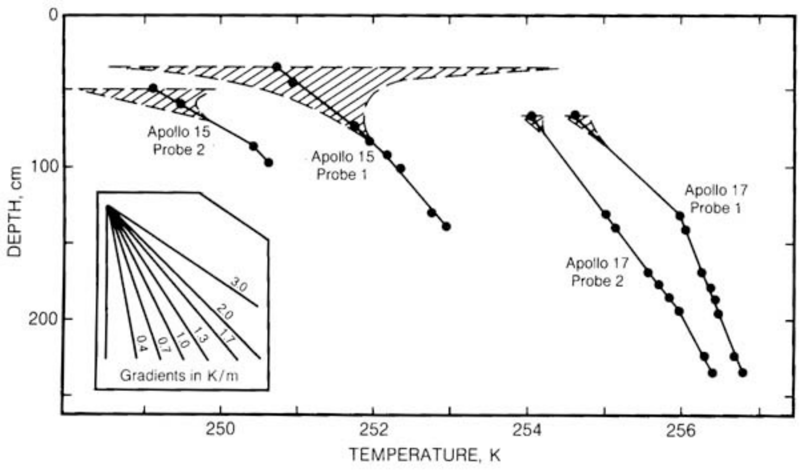
Constrains:

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



Key challenges:

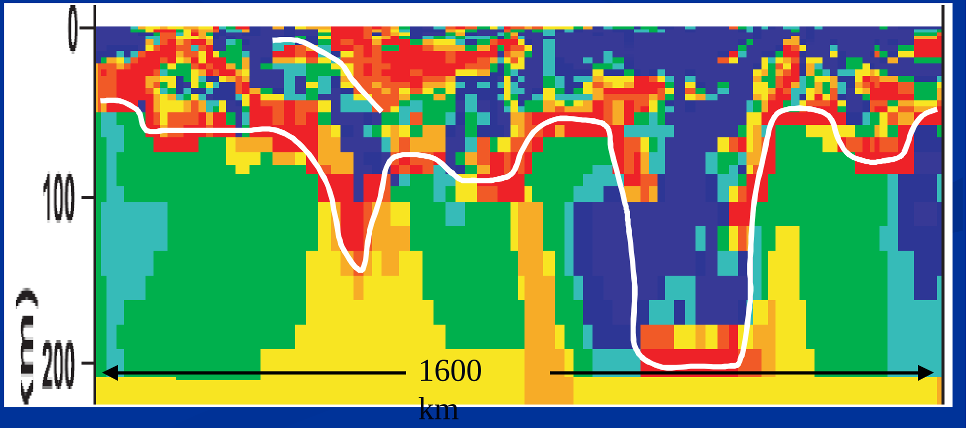
- Measuring the thermal gradient beneath the annual thermal wave, at 3-5 m depth.
- Accurately measuring the thermal gradient and conductivity in an extremely low conductivity environment where self-heating is an issue.
- Effects of local topography
- Long-term fluctuations of the surface temperature 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



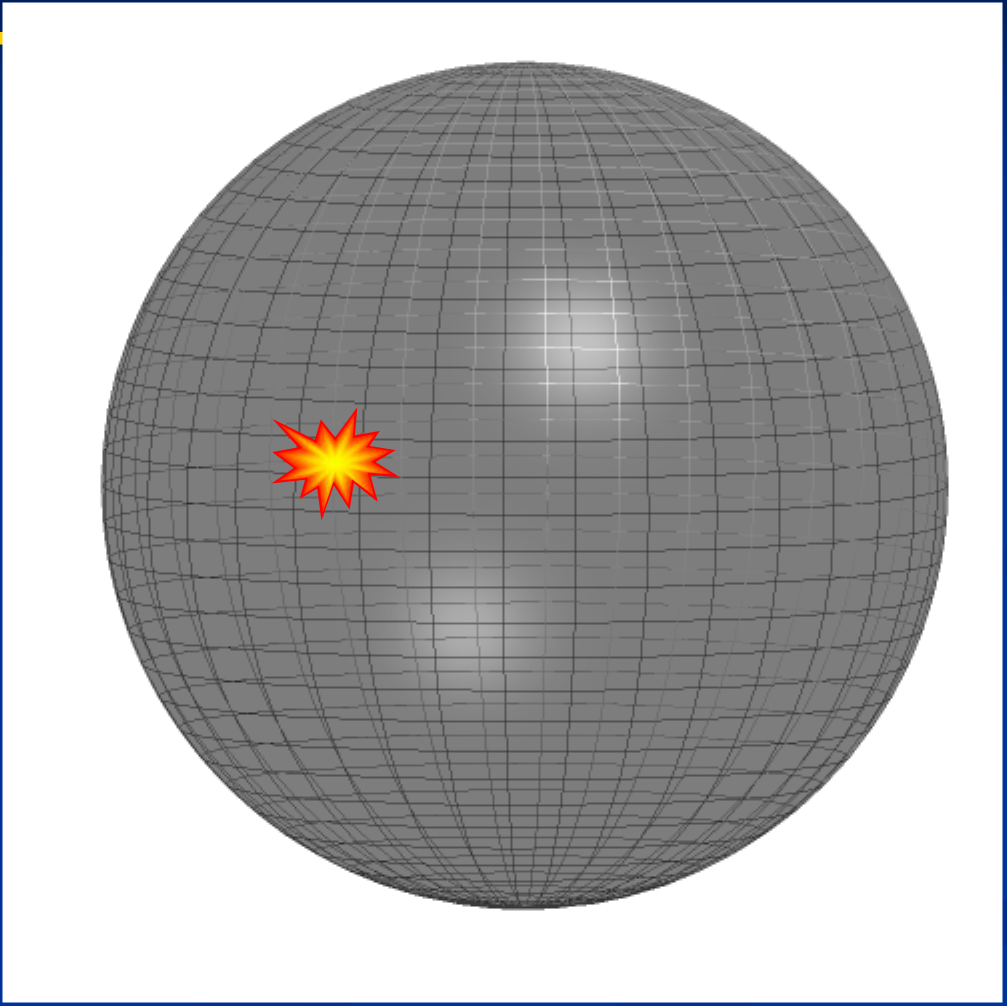
How Many Stations for How Long?

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

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

Locating a Marsquake

Assume a quake on a homogeneous planet…

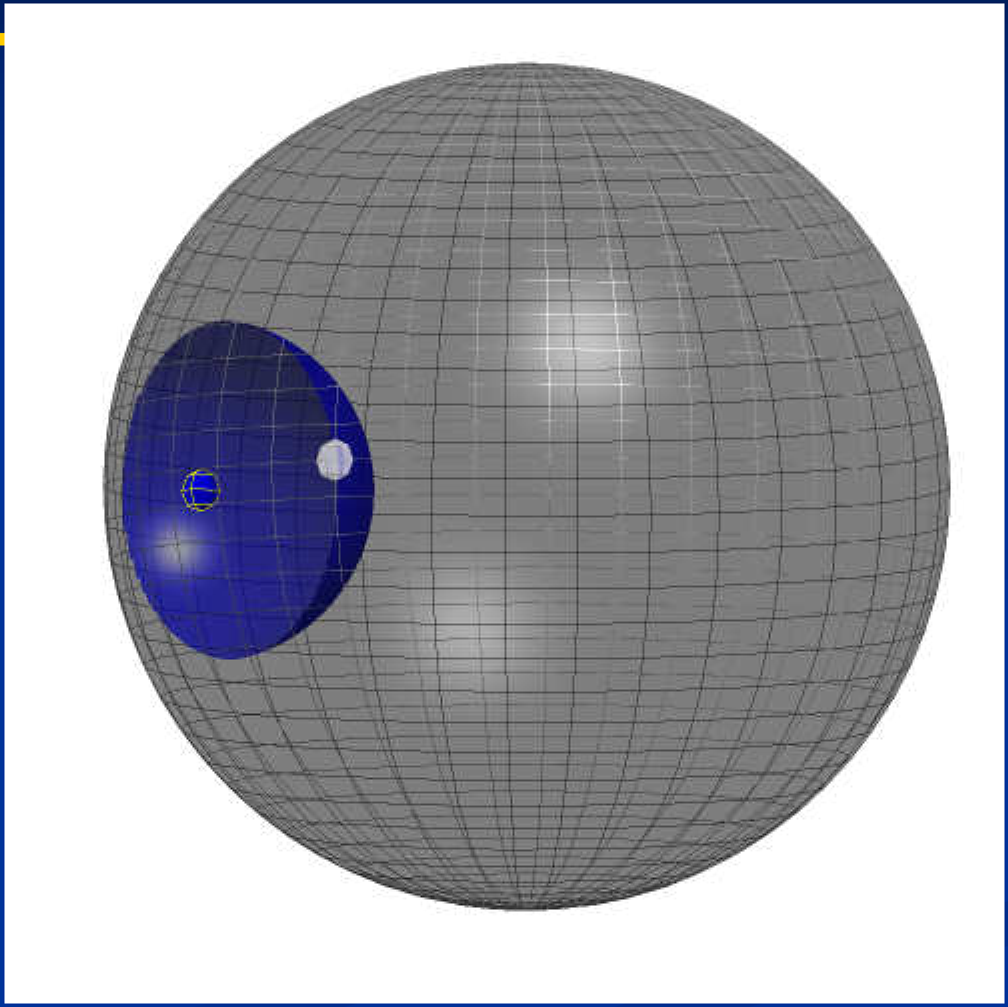


Locating a Marsquake

Assume a quake on a homogeneous planet…

1 Station:

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



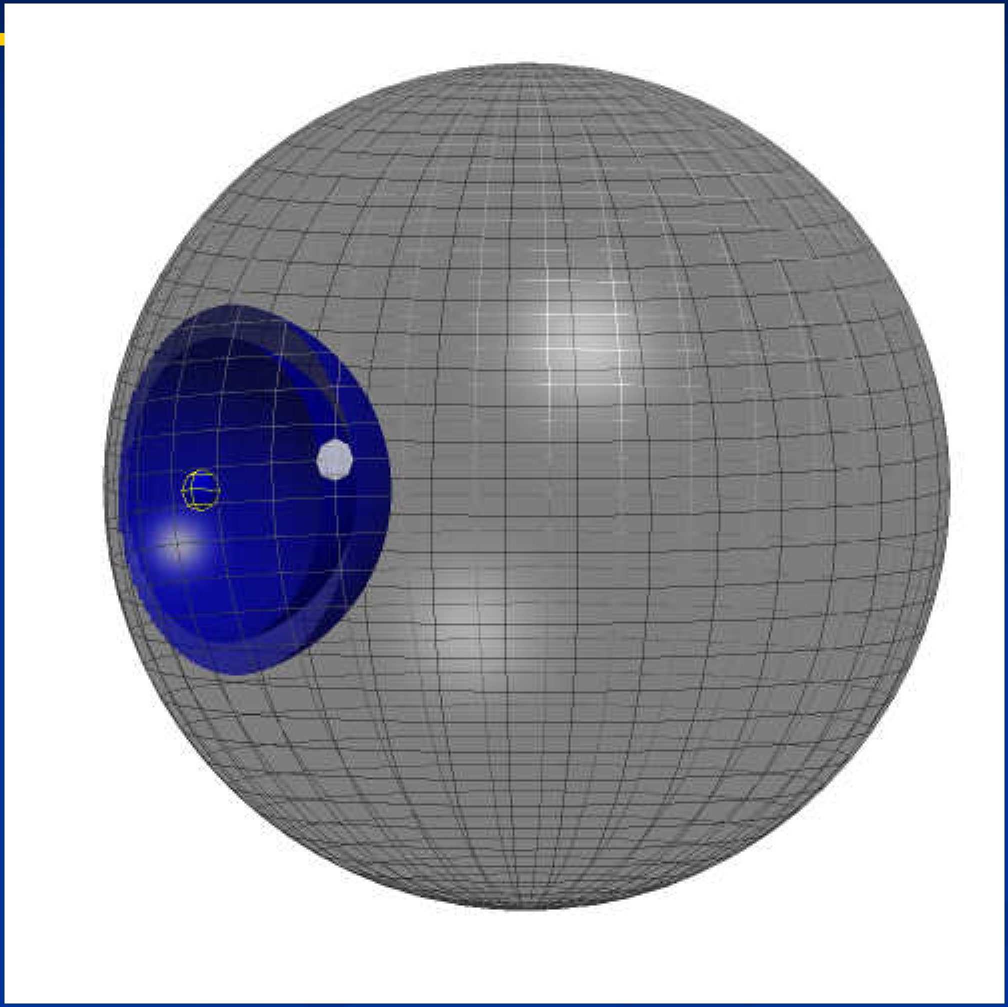
Locating a Marsquake

Assume a quake on a homogeneous planet…

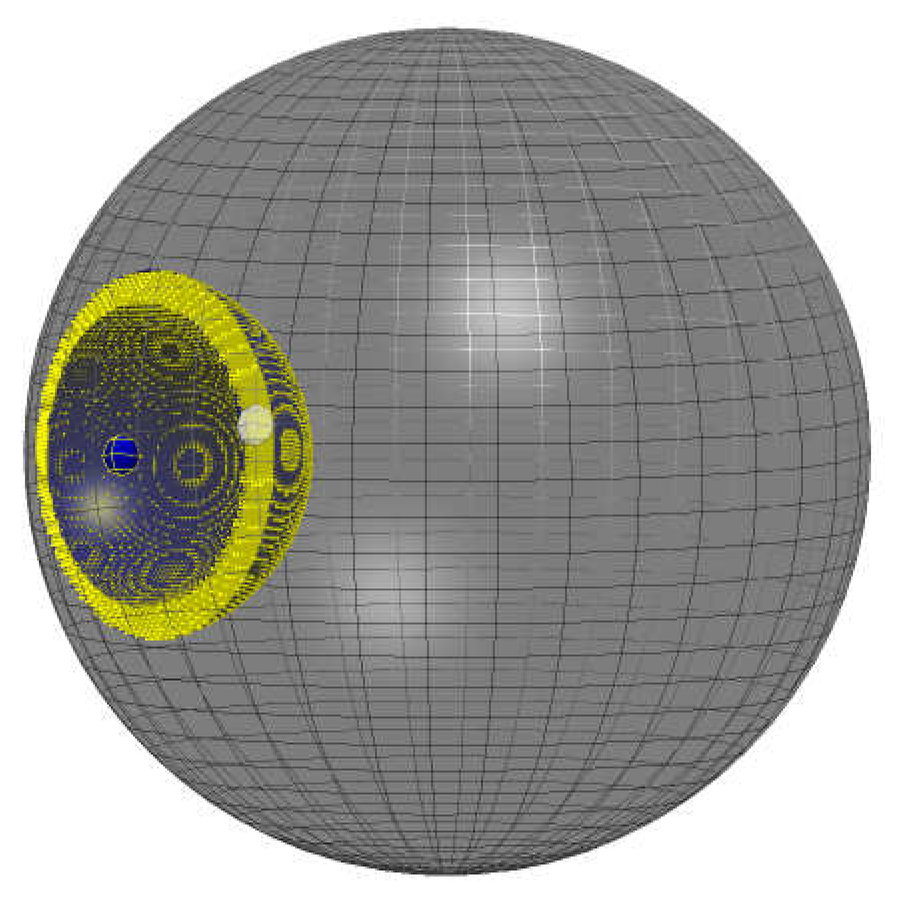
1 Station:

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.



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.

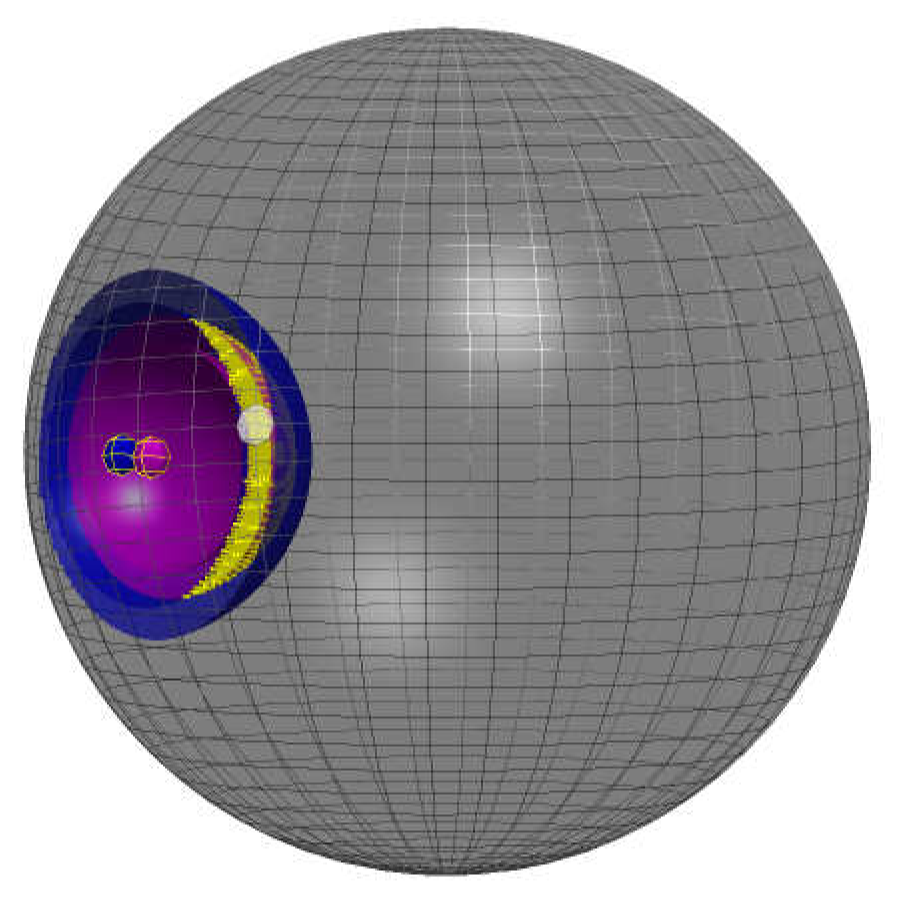
All points within this shell (**yellow**) are candidate locations and cannot be distinguished any further without more data.

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.

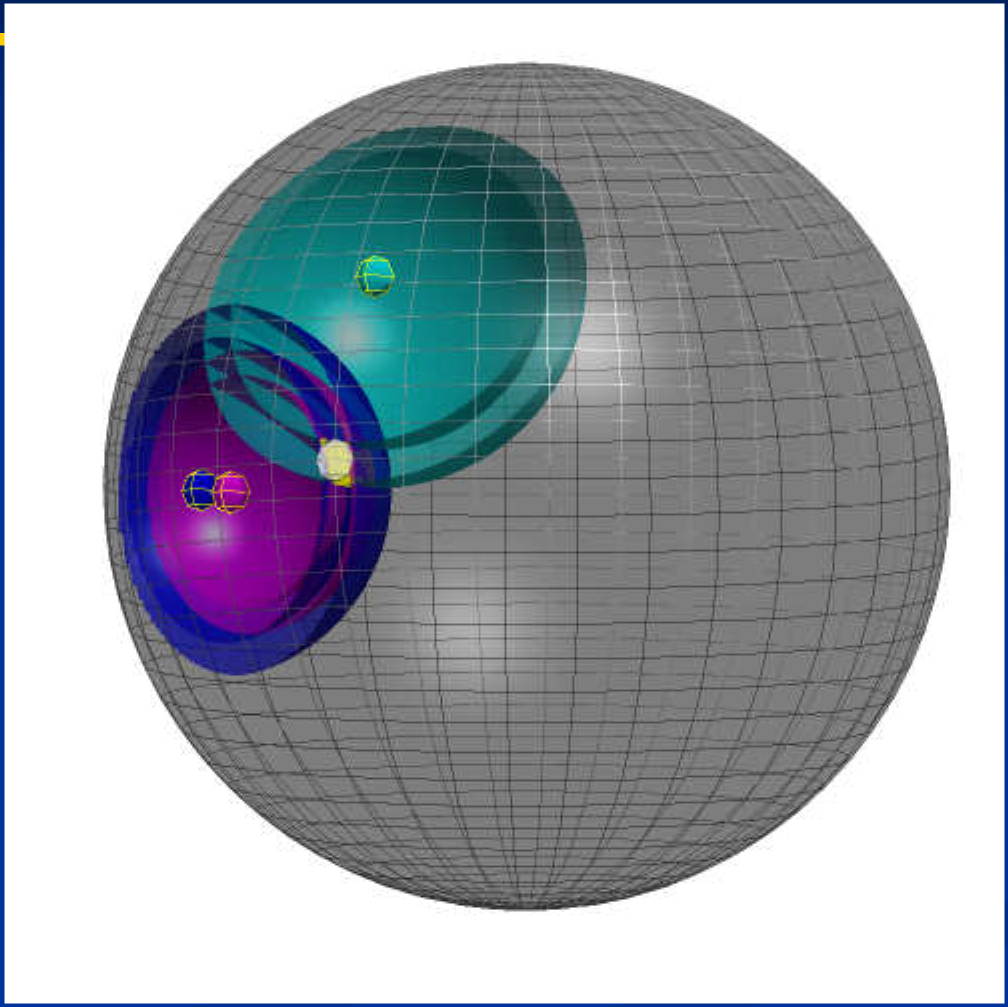


Locating a Marsquake

Assume a quake on a homogeneous planet…

3 Stations:

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

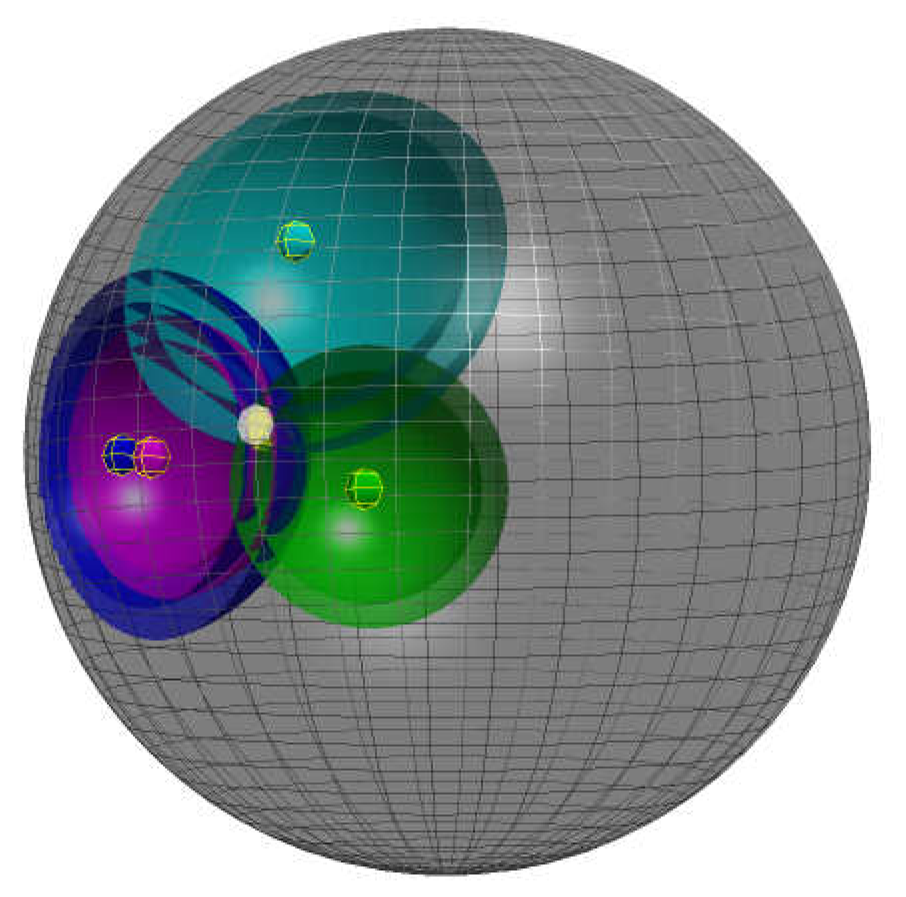


Locating a Marsquake

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.



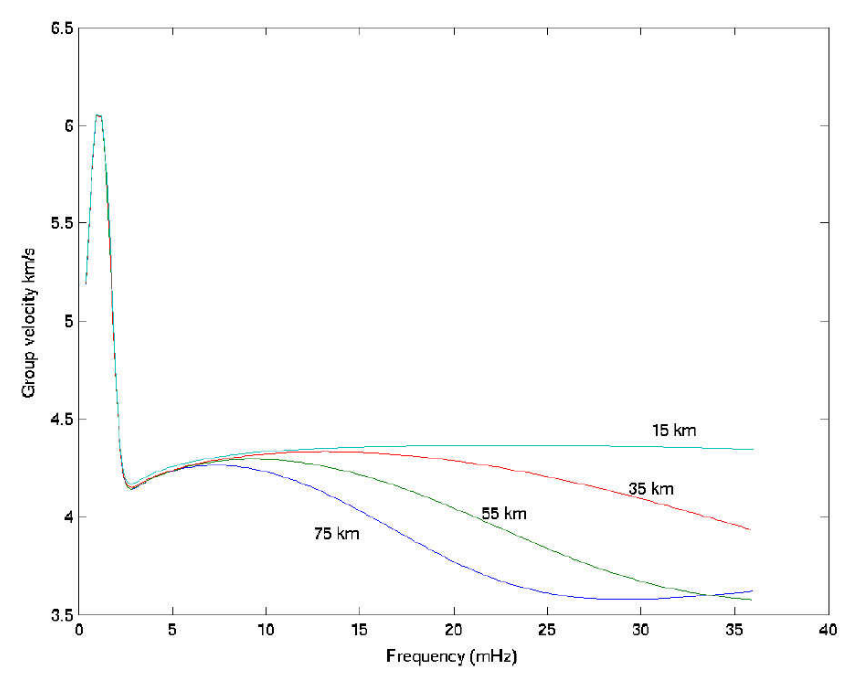
Number of Stations for Seismology

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

But …

- With a non-uniform velocity it is possible to derive a velocity profile from body wave arrivals whose uncertainty decreases with larger number of events using fewer than 3 stations.
- There are a number of techniques for using dual-station or even single-station data to obtain interior structure information.

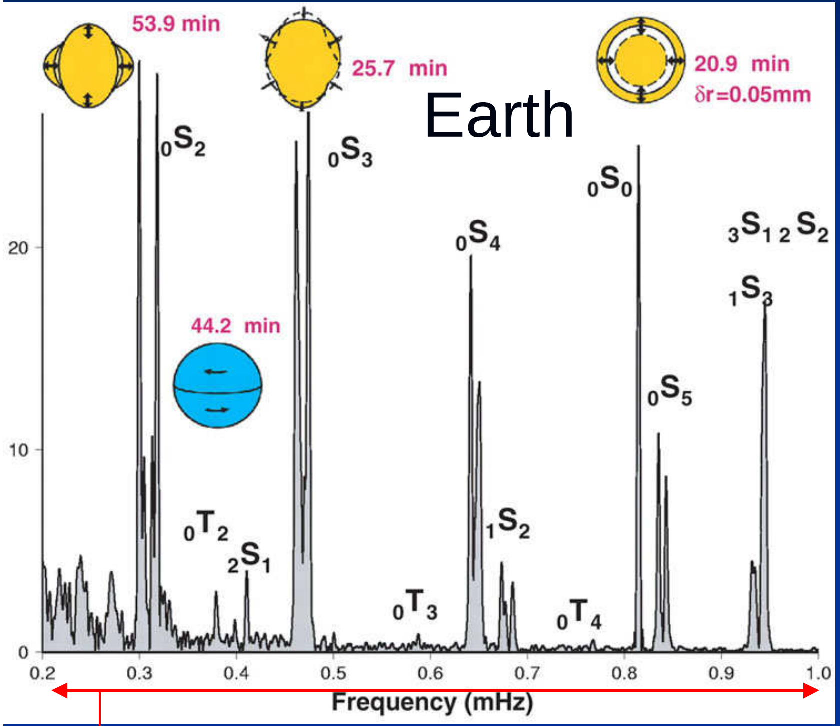
Surface Wave Seismology

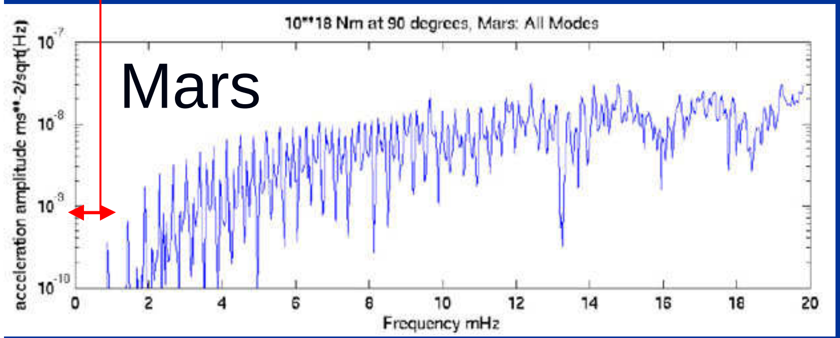


Simulated surface wave dispersions curves for different crustal thicknesses on Mars.

- **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 crust and upper mantle structure information from 2 stations (or even a single station using the arrivals of the R1, R2, R3 phases).**
- **Alas, only relatively large quakes (e.g., M > 5) tend to generate surface waves on Earth (perhaps >4 on Mars).**

Normal Mode Seismology





- 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.
- 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

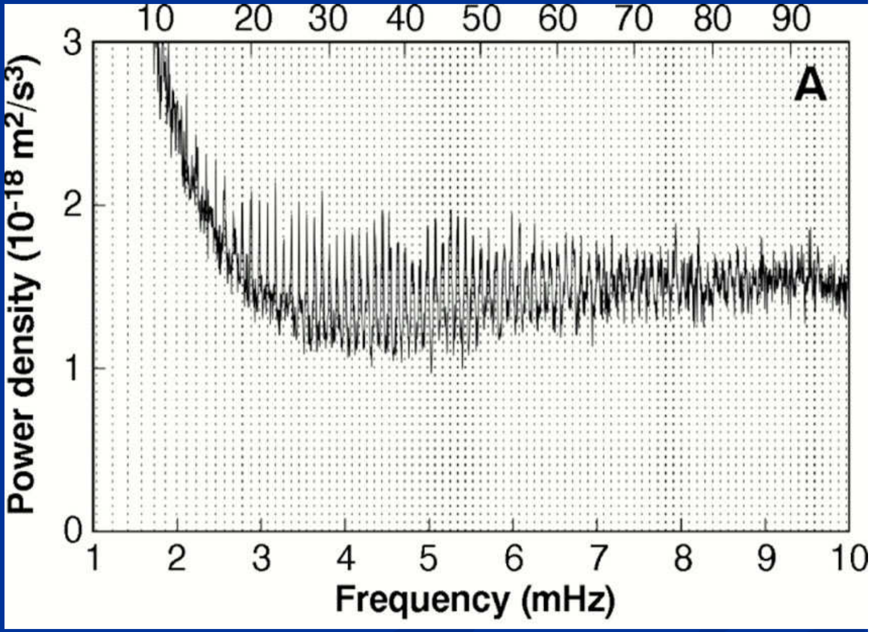
Tidal Response

- **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 single VBB seismometer with ~6 months of recording – no seismic events necessary.**

Noise Techniques – Seismology Without Quakes

Background Noise Spectrum: Earth

- On the Earth, measuring normal mode peaks from event-free data is a well-established technique.
  - Energy is pumped into the vibrational modes through interactions between the surface and the atmosphere/ocean.
  - With about a week of integration, one can produce a normal mode spectrum with peaks relating to the interior structure, completely equivalent to major quake signal analysis.

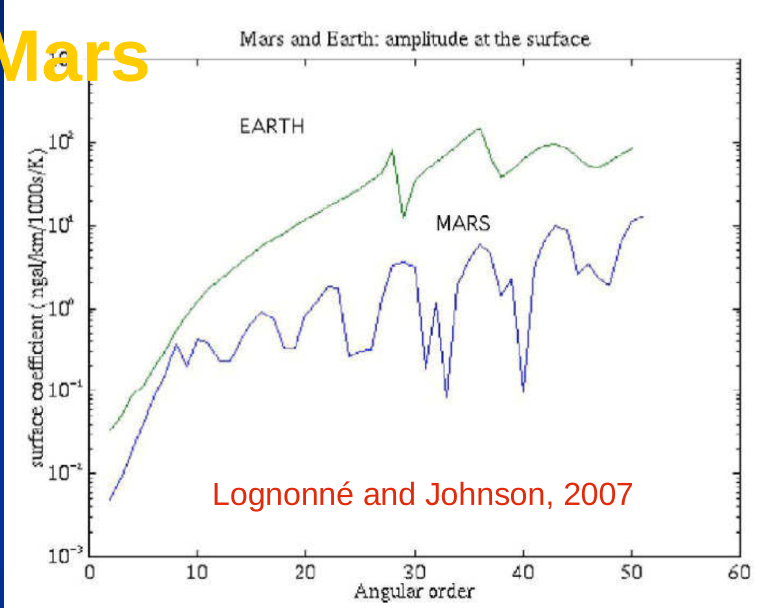


Suda et al., 1998

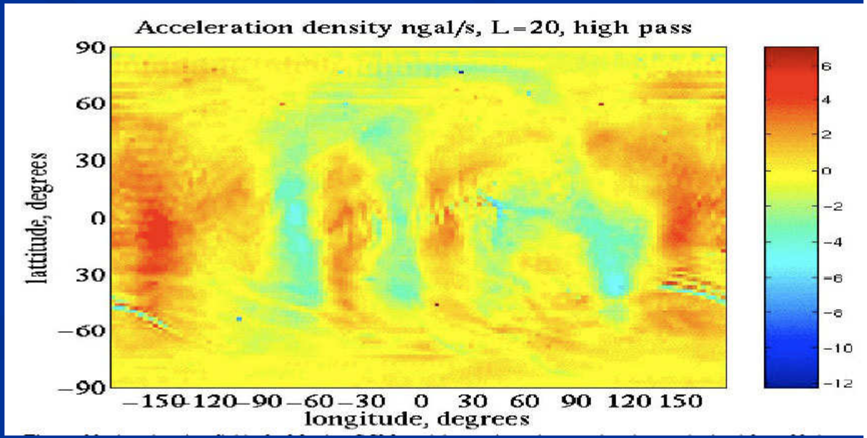
Noise Techniques – Seismology Without Quakes

Background Noise Spectrum: Mars

- The excitation for Mars can be calculated using atmospheric physics and GCMs
  - No ocean on Mars, but still have reasonably efficient transfer of energy from atmosphere to solid planet, especially at lowest frequencies.
  - With current seismometer technology, this would be resolved with ~one year of observation.
- Requires only one station



Lognonné and Johnson, 2007



Noise Techniques –
Seismology Without Quakes

Noise Correlation

- The cross-correlation of noise between two points can be shown to contain all the Green’s function information
    - Essentially, the noise stochastically constructively interferes equivalently to surface waves, and the transport of seismic energy between two points is similarly dispersive.
- This techniques is revolutionizing modern terrestrial seismology
- Requires only two stations

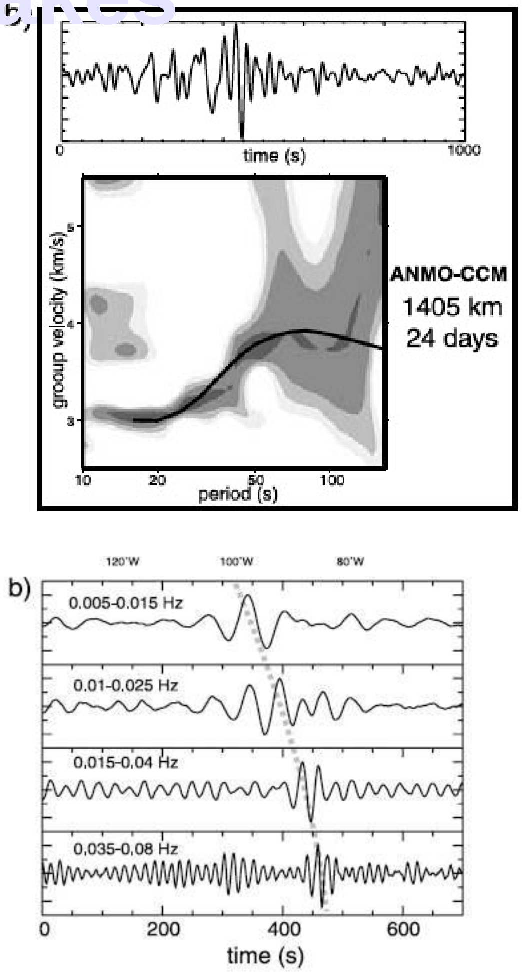


Figure 1. (a) Map showing the station location. (b) Cross-correlations of vertical-component records bandpassed with different filters as indicated in top left corners of each frame. Gray dotted line emphasizes the dispersion of the emerging signal.

Shapiro and Campillo, 2004

Other Single-Station Seismic Techniques

- **Impact Events**
  - Impacts have distinctive seismic signature
  - Can expect detection of order 100 events/yr (over 1700 detected by Apollo).
  - Location of impact maybe determined from orbital imaging, leaving only *v* and *t* as unknowns.
  - Time may be detected electromagnetically.
- **P – S**
  - Time interval between P and S arrival can be used to derive distance and event time (requires velocity model)
- **Polarization Analysis (e.g., First Motion)**
  - 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)
- **Receiver Function Analysis**
  - Can use P-S phase conversion of teleseismic (near-vertical) signals at the crust/mantle boundary to derive crustal structure from correlation of V and H components

How Many Stations for Seismology?

- **Four stations are the minimum required to “fully” address the seismology objectives for interior structure.**
  - Allows for the robust inversion of travel times for interior structure without a priori assumptions.
  - All single-station techniques are available, and can begin to address lateral variations.
  - Provides reasonably complete global coverage.

How Many Stations for Seismology?

- **One station** should provide important constraints on interior structure.
    - There are multiple techniques for extracting important interior information from seismic measurements at a single station.
    - It would be of great value as a "pathfinder" for a full network, indicating location and level of seismicity, and character of seismic signals and noise in this unexplored environment.
- 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.
- Given our nearly complete ignorance of the interior, even a modest amount of information will be valuable.

How Many Stations for Seismology?

- **Two stations** represent a major increase in science value.
  - Allows the unambiguous recognition of seismic signals through correlation of arrivals.
  - Significantly decreases the ambiguity of event locations (essentially two-fold ambiguity).
  - Allows the straightforward application of noise correlation and surface wave dispersion techniques.

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

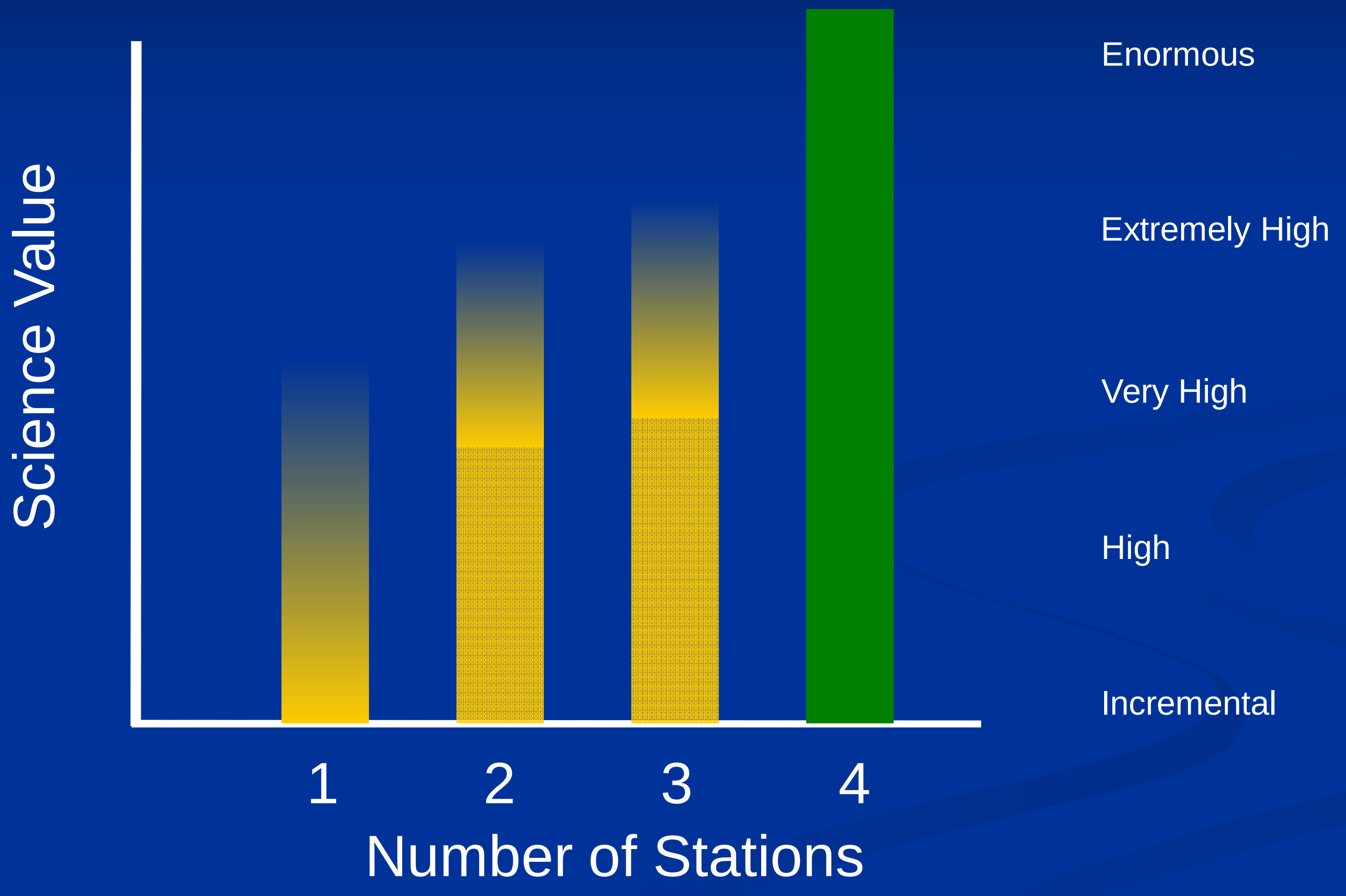
How Many Stations for Precision Tracking?

- 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 expected seismic activity 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.
- Two stations, with well-installed, very-broad-band seismometers, could substantially address the network objectives.
- One such station would provide key information on interior structure and processes.