SOLAR-SYSTEM DYNAMICS AND TESTS OF GENERAL RELATIVITY WITH PLANETARY LASER RANGING

J.F. Chandler, M.R. Pearlman, R.D. Reasenberg

SAO, Harvard-Smithsonian Center for Astrophysics

and J. J. Degnan

Sigma Space Corporation

Science Questions

- Does the strength of gravity change with time?
- At what level and in what respects will general relativity fail?
  - Shapiro Time Delay: at what level ?

Solar-System Ranging

- Radar
  - Topography mapping (10 km)
  - Fine structure (craters, etc. 1 km)
  - Closure points (imperfect)
- Spacecraft ranging
  - Viking landers (5m)
  - Mars Pathfinder (10m)
- Planetary Laser Ranging (1 to 100 mm)

Object of Study

- Investigate scientific value of ranging data with accuracy from 1 to 100 mm.
- Investigate scheduling considerations.
  - Sun avoidance angle.
  - Duration

Design of Study

- Earth-Mars ranging.
  - Single station on each.
  - Transparent bodies (simplifies scheduling).
- Covariance studies are optimistic.
- Use extensive model with large set of parameters to estimate.
- Condition study by using existing diverse set of solar-system data.

Solar-System Analysis Model

- Masses & Orbital elements (63)
- Orientation (364, Earth; 6, Moon; 9, Mars)
- Station coordinates (30)
- Target coordinates (12,Moon; 9, Mars)
- Topography (566, Mercury; 444, Venus)
- Moon mass distribution (9)
- Measurement biases (24)
- Other (10)
  - Asteroid class densities
  - Sun mass distribution (J_2)
  - Earth-Moon tides
  - Interplanetary plasma density

Supporting Data Sets

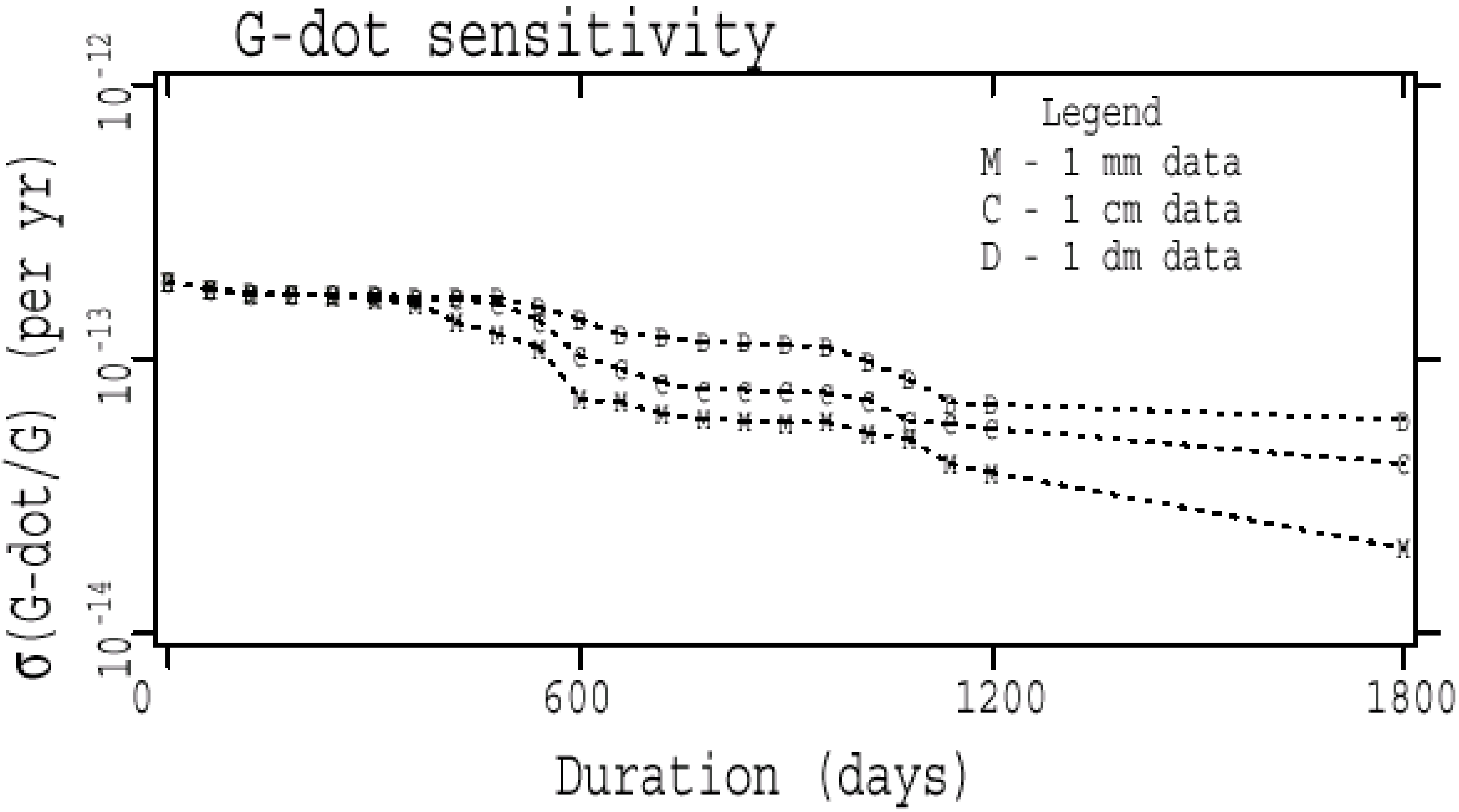
- Mariner 9 normal points (185)
- Viking Lander delays (1280)
- Pathfinder delays (90)
- Outer planet normal points (6)
- Mercury radar delays (8054)
- Venus radar delays (5674)
- LLR normal points (13,538)

G-dot -- Introduction

- Does G, measured in atomic units, vary with time?
- Dirac (1938): Large Numbers Hypothesis.
- Modern theories.

$$\frac{2\dot{G}}{G} \approx -\frac{2\dot{a}}{a} \approx -\frac{\dot{P}}{P} \approx \frac{\dot{n}}{n} \qquad \text{Thus, } \Delta M \propto t^2$$

G-dot -- Results

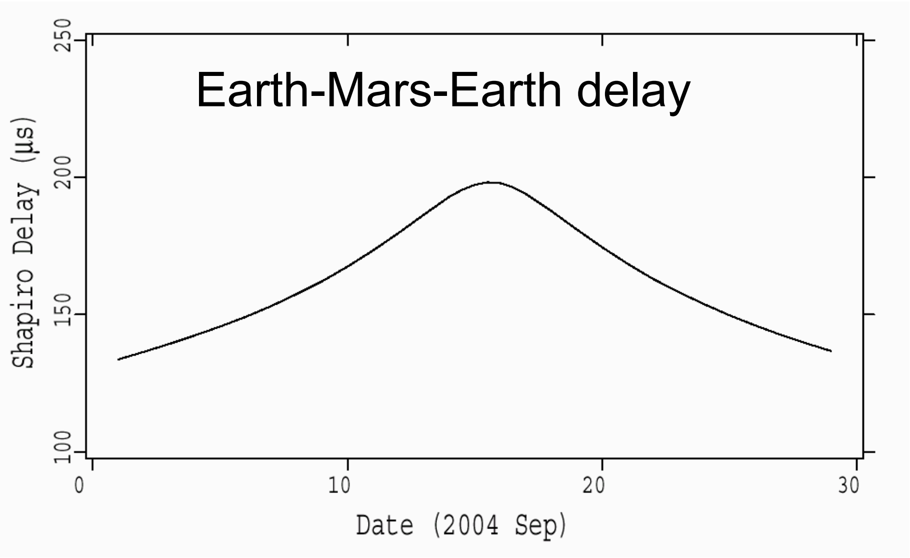


Shapiro Time Delay

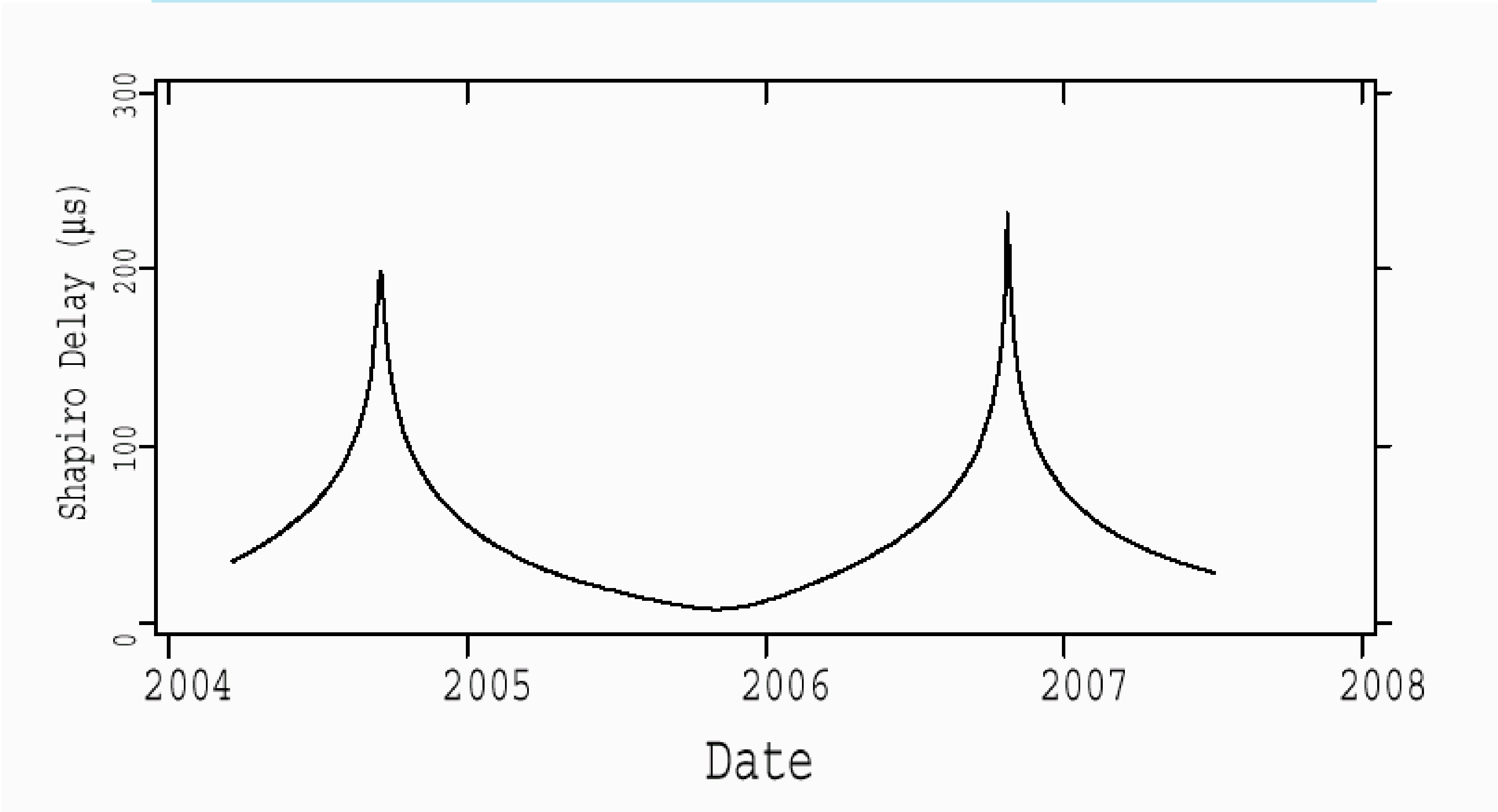
$$\Delta\tau = \frac{2r_0}{c}\frac{1+\gamma}{2}\ln\left(\frac{r_e + r_p + R}{r_e + r_p - R}\right) \approx \frac{2r_0}{c}\frac{1+\gamma}{2}\ln\left(\frac{4r_e r_p}{d^2}\right)$$

$$r_0 \equiv 2GM_\odot / c^2 \approx 1.5\text{km}$$

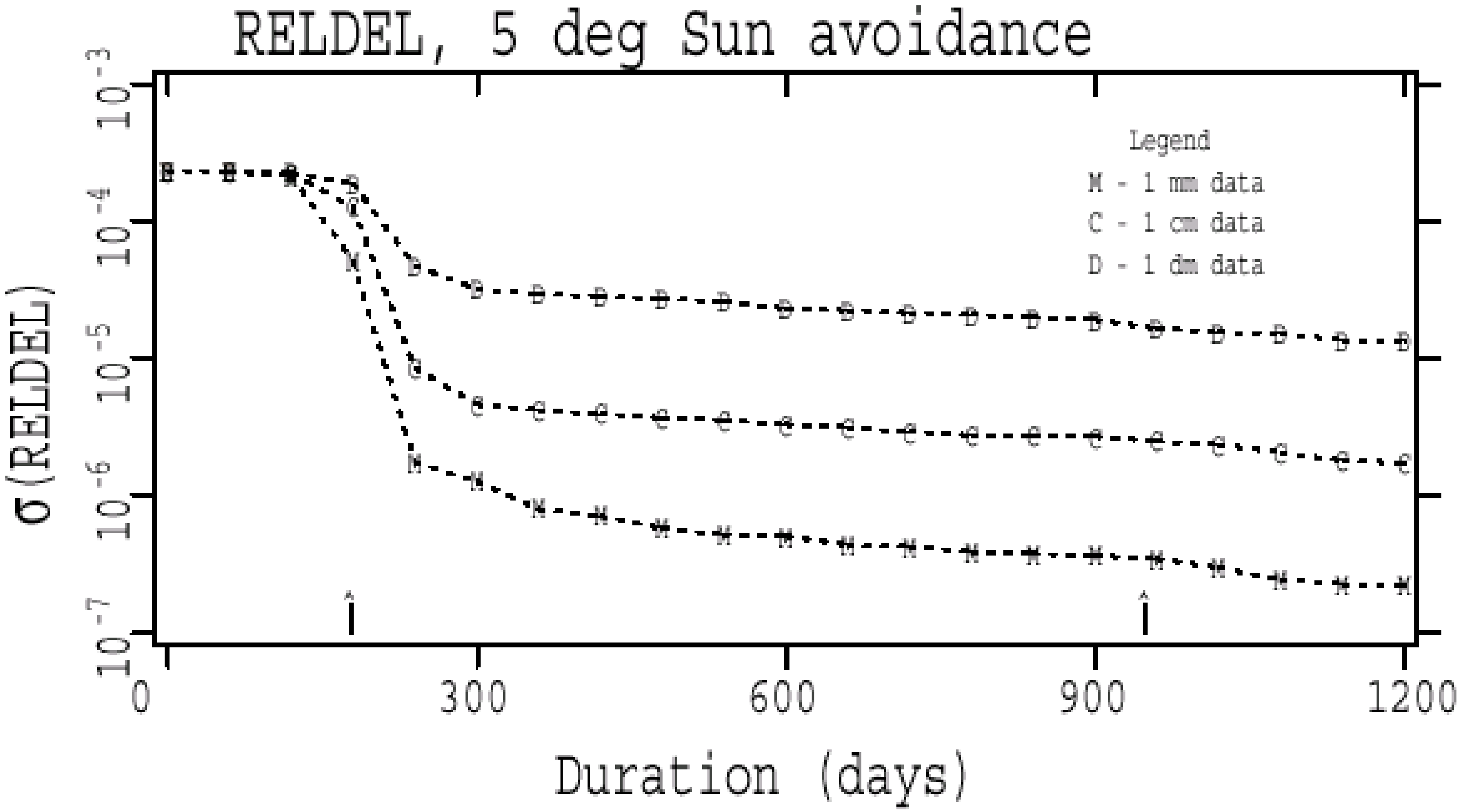
$$2\Delta\tau\,(\text{at solar limb}) \approx 250\,\mu\text{s}$$



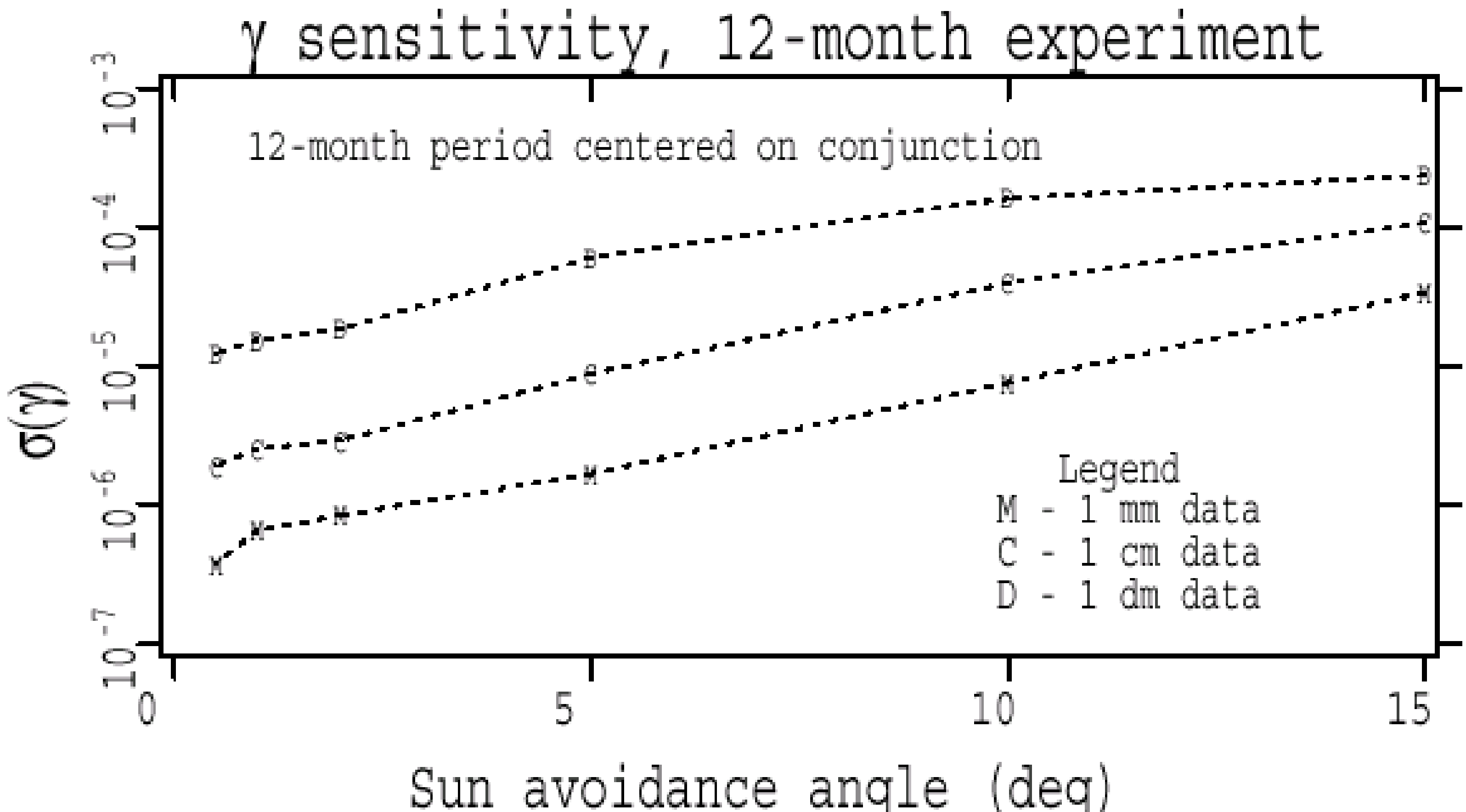
Shapiro Effect
(Earth-Mars-Earth Delay)



Delay Results (RELDEL)



Delay Results (Min. Angle)

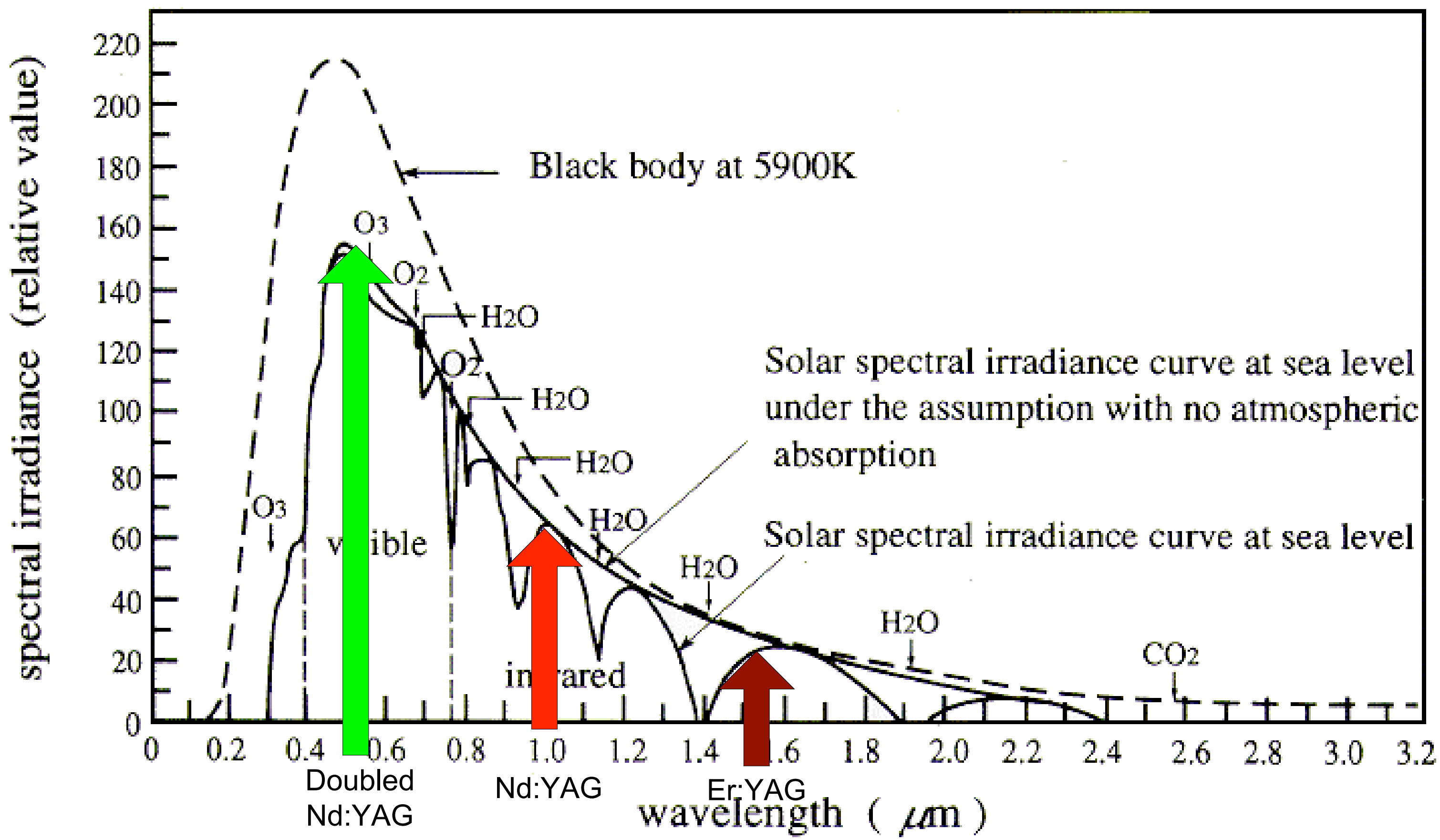


Working Close to the Sun: Problems

- Optical damage to detector
- Excessive solar heating of instrument
- Excessive background noise which obscures transponder signal

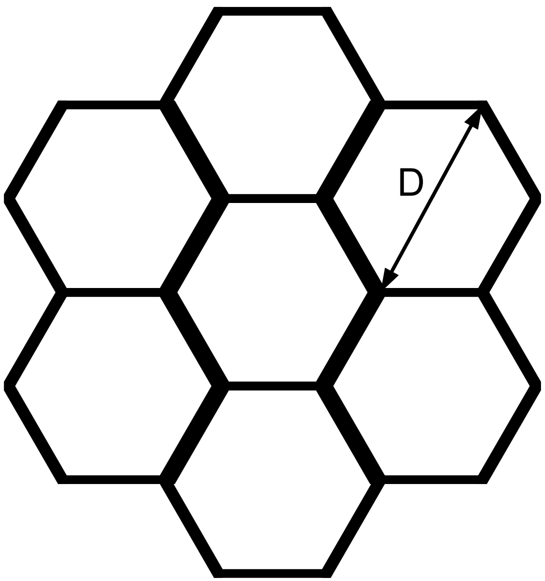
Working Close to the Sun: Possible Solutions

- Accurate navigation and attitude information plus Sun avoidance software
- Choose operating wavelength with good atmospheric transmission far from the solar blackbody peak
  - Diode-pumped, subnanosecond pulse, Er:YAG microchip lasers and fiber amplifiers emit at 1550 nm where there is excellent atmospheric transmission
  - Fast photon-counting PMT's exist but low QE (~0.8%)
- Reflect most or all solar irradiance from telescope surfaces and entrance window
  - "cold mirror" window reflects the visible and transmits the infrared
  - "white" surfaces on telescope exterior reflect most of the Sun's radiation
- Filter out residual visible/NIR light
  - Use primary and secondary "hot mirrors" which reflect infrared and transmit residual visible light to heat-sinked absorbers decoupled from the optical bench
- Aggressive stray light control
  - Light tight receiver boxes and/or light tubes
  - Narrow spatial field of view
  - Narrow bandpass filters
  - Internal honeycomb grids



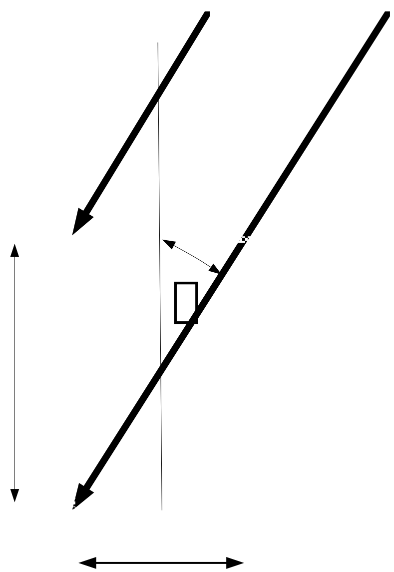
Comparison of spectral irradiance of solar light at sea level with black body radiation

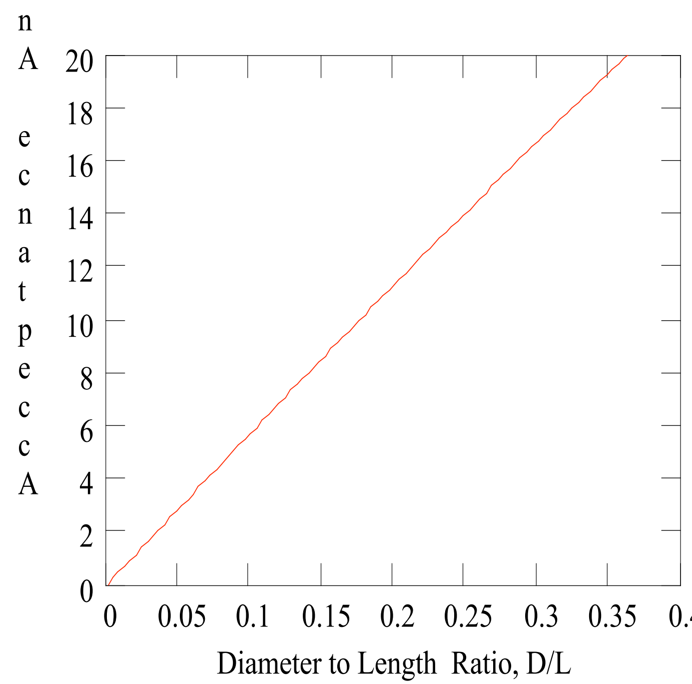
Honeycomb Light Baffle



Front View

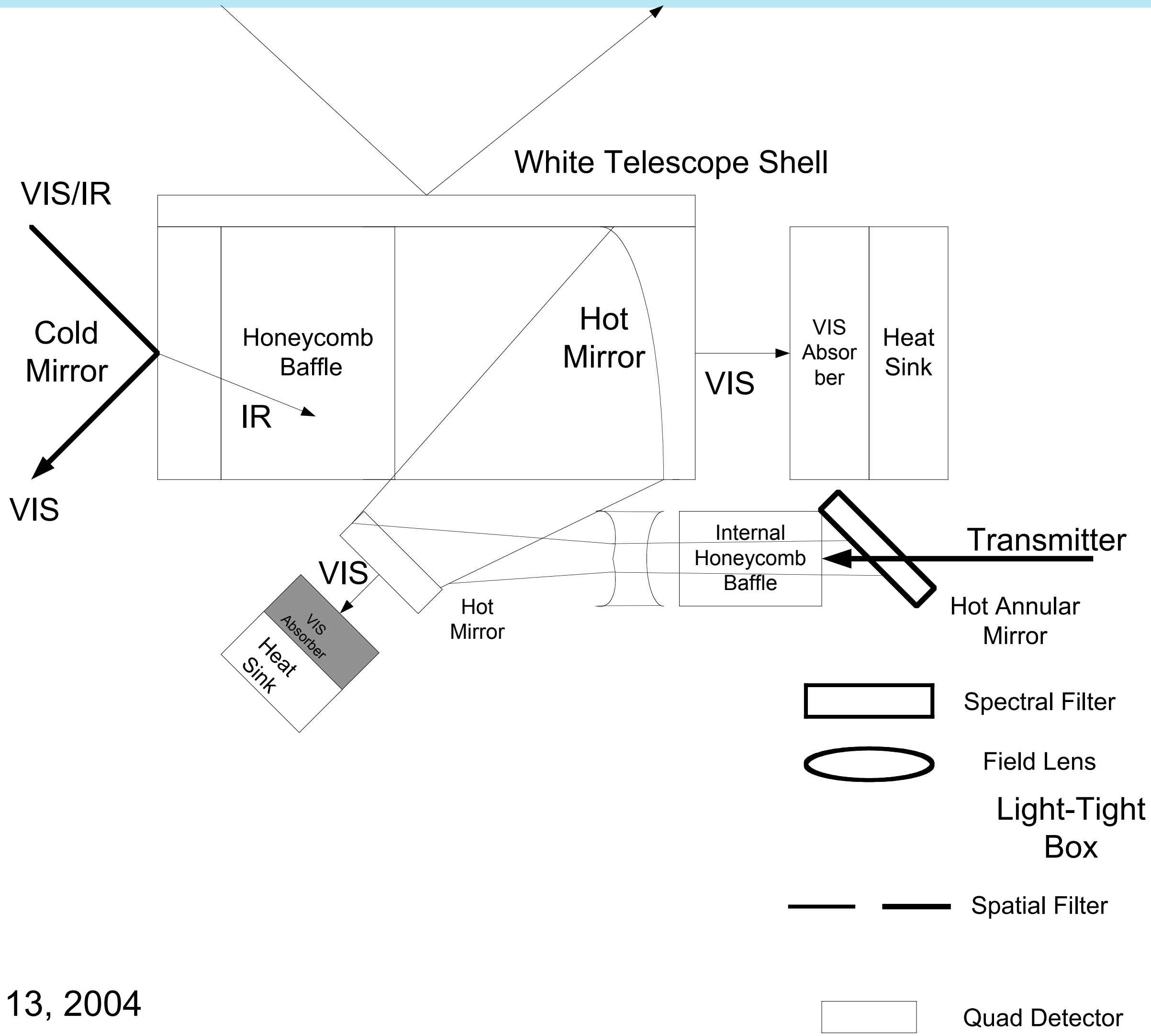
Side View of Individual Cell





$$\theta_{max} = \arctan\left(\frac{D}{L}\right)$$

Possible Optical Configuration



Conclusions

- Planetary Laser Ranging offers significant potential for improving tests of gravity.
- For the Shapiro Time Delay, it is important for the instruments to be able to work to within a small angle of the solar limb.
- More extensive studies are warranted.