Gravity Probe-B - An experiment in frame dragging

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Principle-Geodetic effect and frame dragging

- GPB was designed to test two effects, the geodetic effect and frame dragging
- Geodetic effect is the small angle by which the earth warps the local space time, this can be measured by a body orbitting the earth at a distance r at an angle **θ** to the orbital plane. The angular velocity where $\omega^2 = \frac{m}{r^3\beta}$.

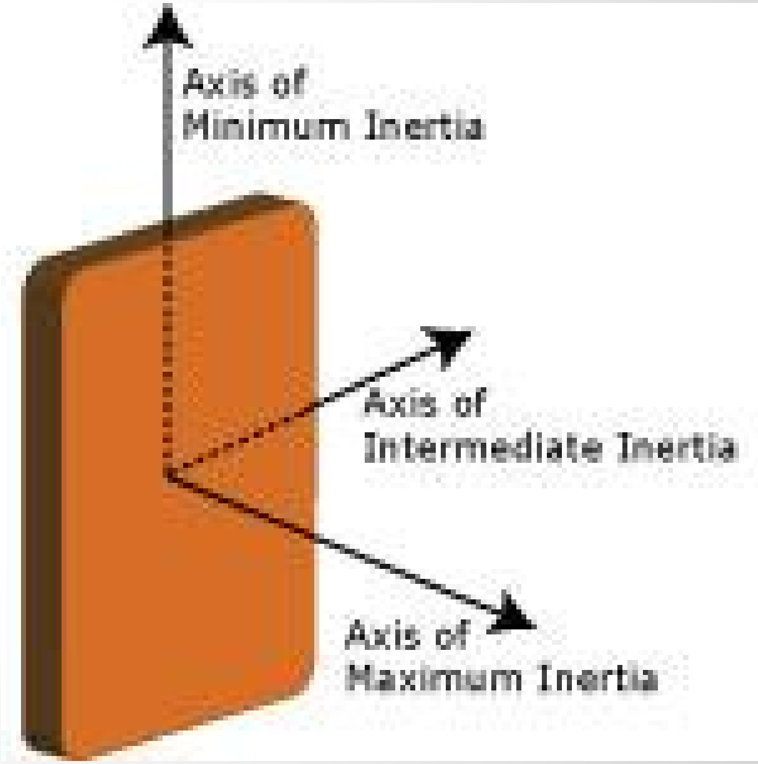
  $\beta = \sin^2(\theta)$.
- Frame dragging is the effect where a rotating body drags the warped space time around it along with its rotation rate.
- To measure these effects accurately the gyroscopes needed extraordinary stability and therefore the space based component of the mission.

Video

Polhodes-- what are they..

- There are three axes of moment of inertia, the axis of minimum inertia, the axis of intermediate inertia and the axis of maximum inertia.
- An ideal rotation of the body is about the orbit of maximum or minimum inertia, when the body spins about the intermediate axis of inertia, it describes an ellipse rather than a circle and this ellipse is known as the polhode path.
- Even when the body spins about the moment of max or minimum inertia, improper energy distribution about the body can cause polhode motion.
- In this case the polhode motion is one of the error sources.

http://einstein.stanford.edu/Media/Polhode_motion-animation.html



Design

The basic design of the GPB consists of the following components

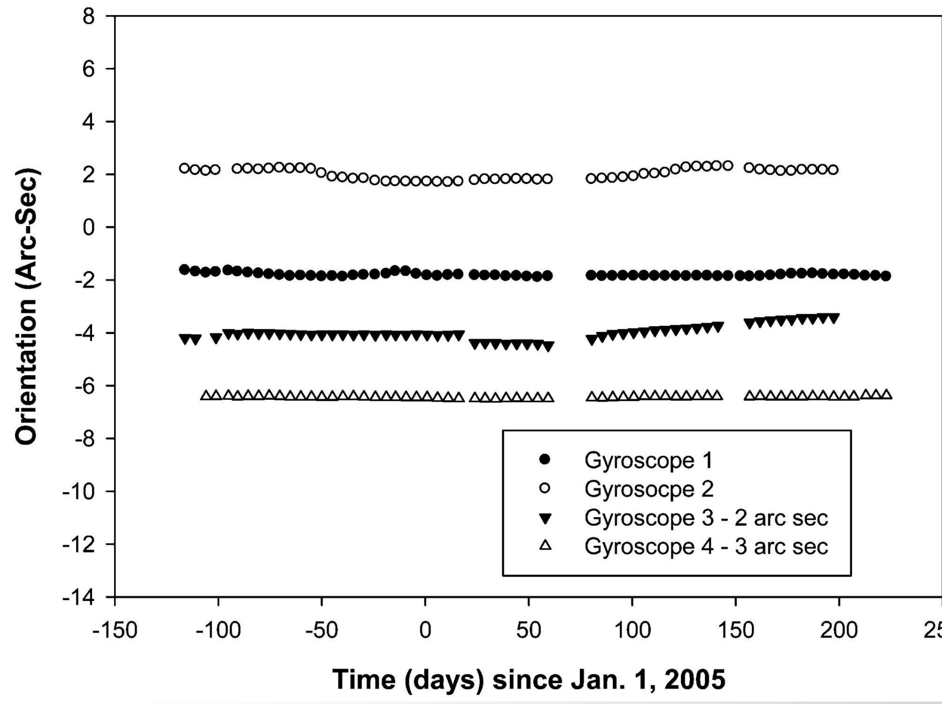
a)Dewar, which is to maintain the low temperatures needed for high precision measurements.

b) The Probe, which contains the heat absorbent windows and the helium adsorbing cyropump assembly

c) The Science instrument assembly which consists of the telescope, the quartz block and the gyros optically bonded together. The Gyros also consist of Superconducting Quantum interference devices that monitor the spin axis orientations of the gyros

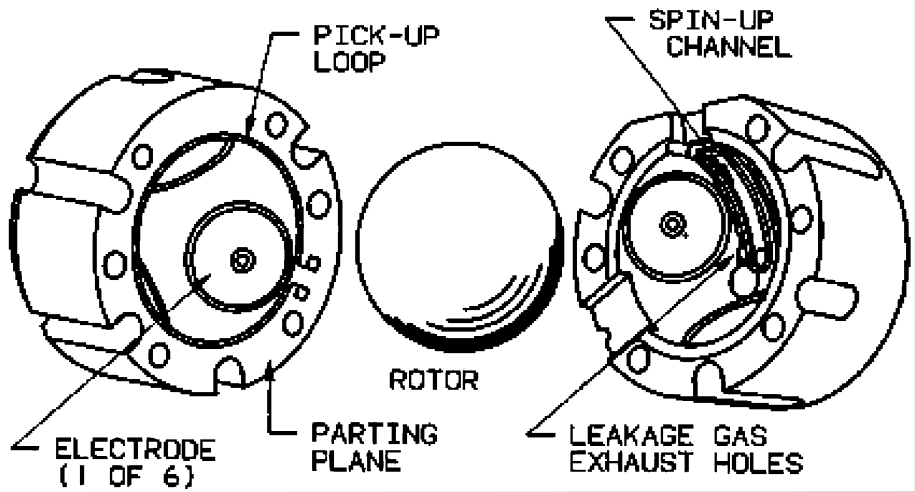
Operation

- The rotors are aligned to the x and y-axis of the telescope system. The calibration phase has the spin axis of the rotors aligned to the direction of the star,i.e where the telescope points.
- The star drift is measured through the year as the telescope orbits the earth.
- The gyroscopes are spin stabilized over a period of time to have spin frequencies of 79.4 ,61.8,82.1 and 64.9 Hz,which changed by 0.01 mHz to 10 mHz over an observation period due to an acceleration of $2x10^{-11}$ m/s^2
- Then based on the drift rate of a perfectly tracking star the science data can be converted to actual frame dragging rates



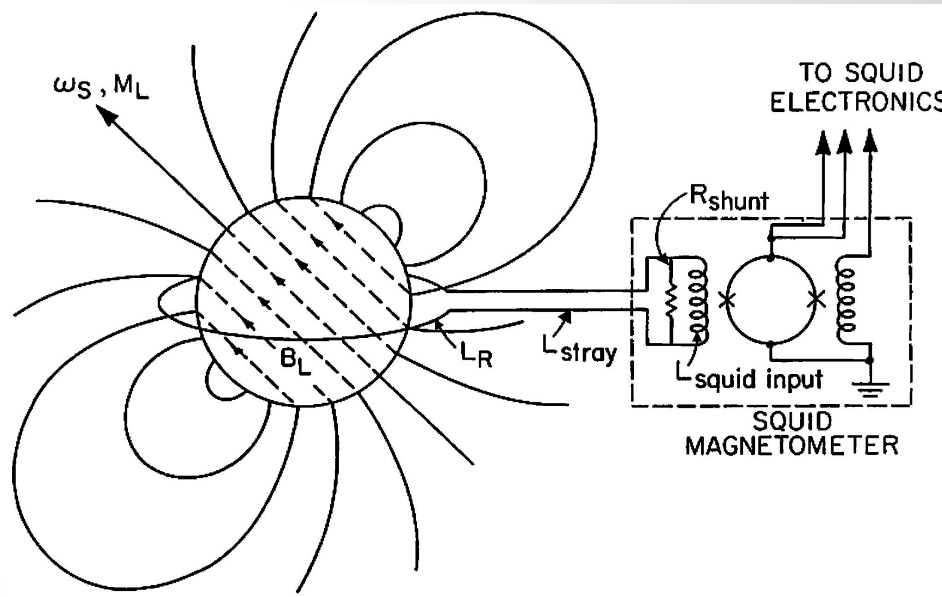
The instrument -Rotors

- The rotors are fused quartz, Homosil material with diameters of 3.94 cm. This is then lapped and rounded to 3.7996 cm with a sphericity of better than 25 nm.
- Each of the spheres were coated with a niobium layer of thickness of 1.3 μm to provide an electrically conducting surface for the electrostatic suspension and for the read out of the London moment. The coating was achieved using sputter deposition.
- The rotors are housed in quartz housing which has a spherical cavity 31μm larger than the radius of the coated rotor, the housing consists of three pairs of electrodes and a gas spin up channel.
- Spin up is achieved using Helium gas passed through the spin up exhaust channel in the housing.
- The pressure from the gas during spin u produced a force of 0.1g on the rotors
- The spin up phase was identified as the highest risk phase of the operation



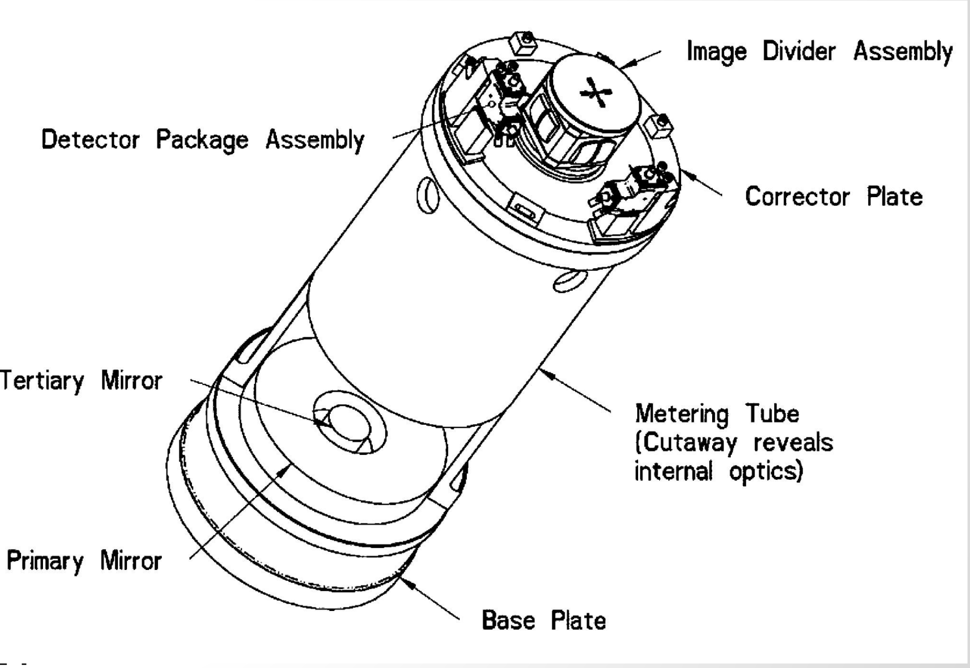
The instrument-Gyroscope readout

- The gyroscope reads the difference between the spin axis and the axis of the magnetic field known as the London moment. By measuring the change in this field we can determine the changes to the gyroscope's orientation.
- At a speed of 4000 RPM the niobium layer produces an equivalent field of 5.7 nT as it becomes a spinning super conductor.
- The gyroscope rotational velocity does not remain constant(contrary to what we assume) but varies along an elliptical path described by the polhode path.
- This is connected to a Superconducting Quantum interference device (SQUID) which reads the magnetic flux produced because of the London moment
- The pick up loop in the image has a voltage induced by a rotating nagnetic field and this is then converted to feedback current which keeps the field constant on the nionbium layers



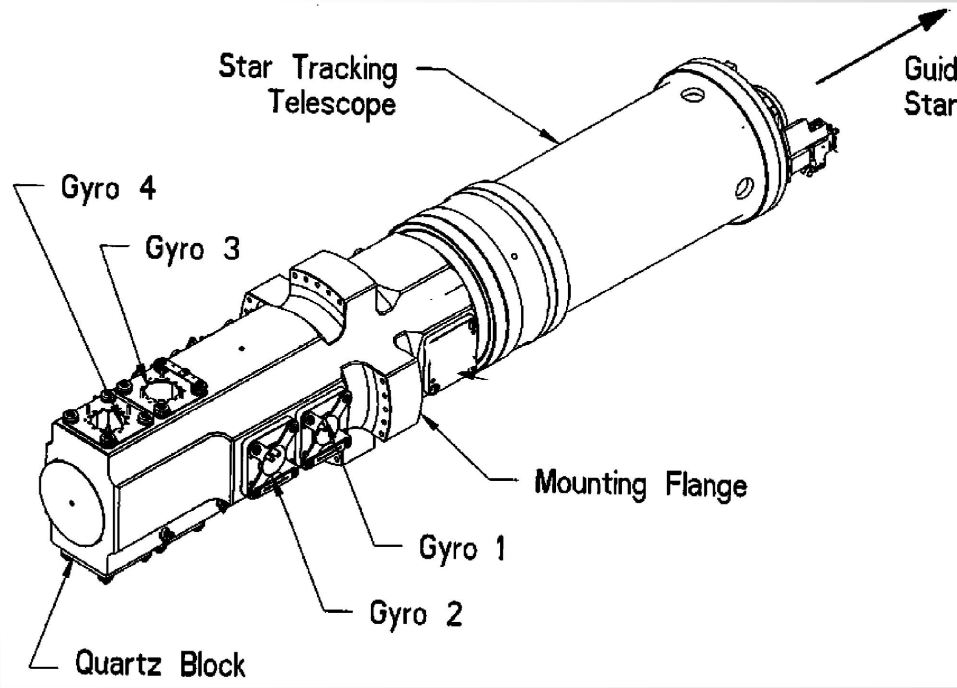
Instrument-the Telescope

- The telescope has an aperture of 14 cm, focal length of 3.8m and field of view of 66 arc seconds.
- The telescope acts as a light detector quite literally with the ima divider dividing the light into 4 part with the image divider assembly where it is split into redundant pho diodes
- The difference in the prism from th light on both sides gives the relativ deviation of the position of the star within 400 marcsecond
- The current is measured using JFE preamplifier and charge locked loop to a range of 11 to 22fA
- The Operating temperature of the telescope is 72K



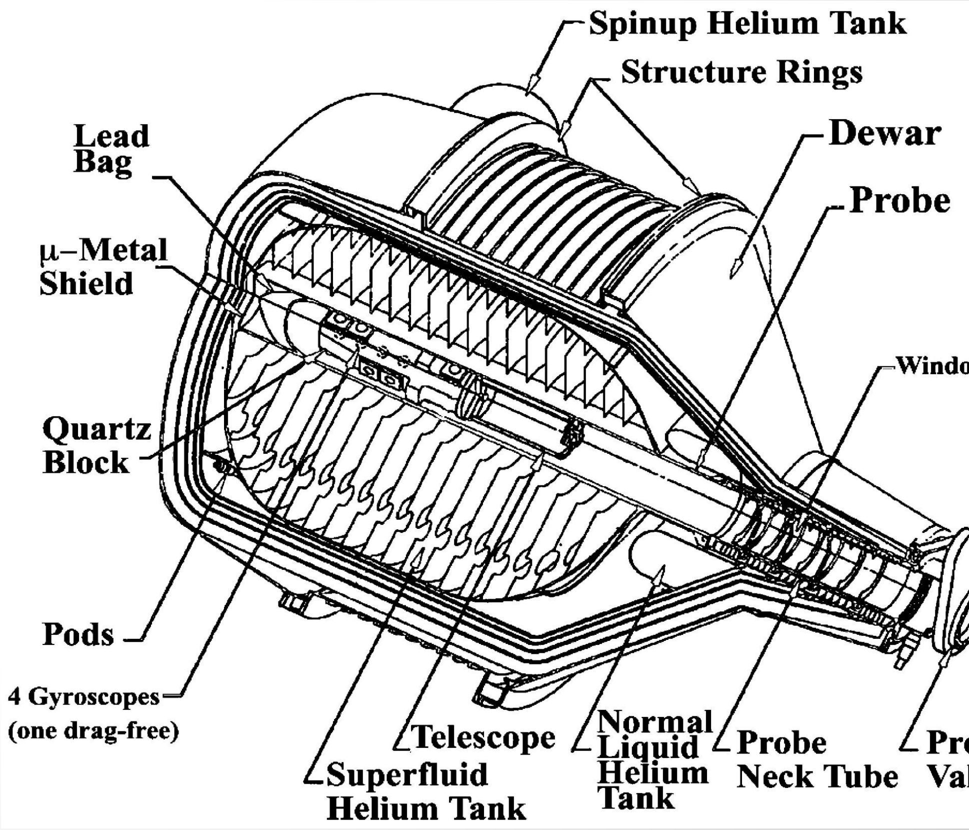
Instrument: Low temperature probe and quartz block meteorology

- The gyroscopes are inserted into a quartz block which is mounted on a low temperature probe.
- The Quartz block is the assembly that holds the gyroscopes and the spin-up helium valves which are used to pump helium into the rotors for spin up.
- The probe contains the feedthrough connectors for the electrostatic suspension and the gas tubes for exhaust of the gas.
- The probe does the important task of maintaining pressure of the spin up helium gas after the gas has been evacuated.
- The quartz block also houses the electrostatic suspension system which suspends the rotors and also regulates the acceleration of the rotors .



The Instrument: Helium Dewar

- The low temperature probe is inserted into a 2300L superfluid liquid-He dewar, which is designed to maintain the science instrument at cryogenic temperatures for 16.5 months.
- It is also used to control the attitude and translation of the space craft, by exhausting boil-off He gas from the super fluid liquid helium exhausted through a porous plug.
- The dewar also ensures that the whole telescope assembly is at an optimum temperature of 1.7K.
- A critical aspect of the Dewar is the shielding of the superconducting rotor's London moment from the magenetic field of the earth

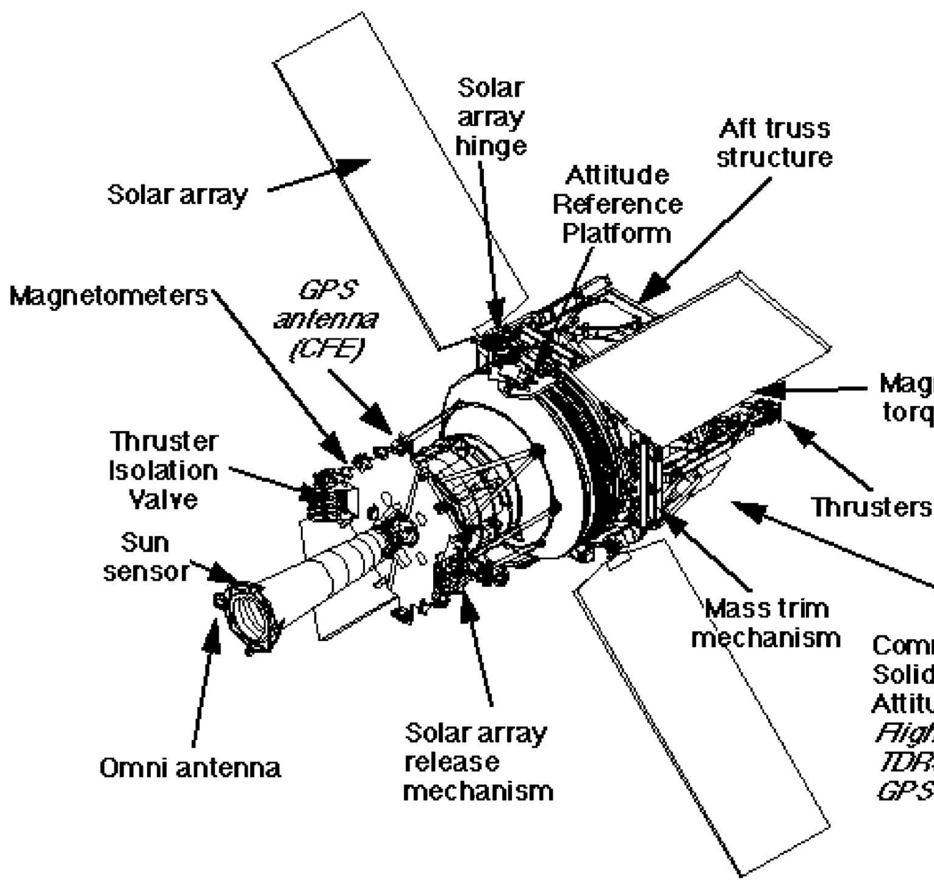


The instrument-Magnetic shielding of the Dewar

- The dewar also functions to reduce the residual magnetic field in the super conducting gyroscopes. The residual magnetic field has to be less than 0.9 nT.
- These requirements within the probe were met by multiple layers of shielding . The first layer of shielding is within the Dewar which is a high permeability magnetic shielding reduces the magnetic field to 0.1 μT.
- A lead tin superconducting shield provides a further attenaution of the external field and the resultant magnetic field is around 0.1 nT
- The magnetic shielding had to be rigorously screened as it attenuates the field by a factor of 10^7 at a distance of 2 m in length by 0.2 m in diameter, the width of the probe .
- further magentic shielding was achieved by inserting cylindrical superconducting niobium shields into the bores of the quartz block which held the gyroscopes.

The instrument-The spacecraft

- The super fluid Helium Dewar is inserted into an aluminium frame which provides the structural framework shown here .
- The outermost window of the low temperature probe which is focussed on the star has two types of shielding a) a sunshade and b) a low temperature shutter which protects the spacecraft from the earth's albedo
- Power is provided by solar panels and batteries and antennas attached to the front and back of the spacecraft
- The spacecraft had to be custom designed so that the balancing is precise and the electronics are thermally conditioned.
- Mass control mechanisms were in place to ensure the principal axes of the telescope and spacecraft were in place
- The space craft is a non gravitationally drag free space craft with the use of drag free gyros on the outside to sense and block out solar radiation and atmospheric jostling

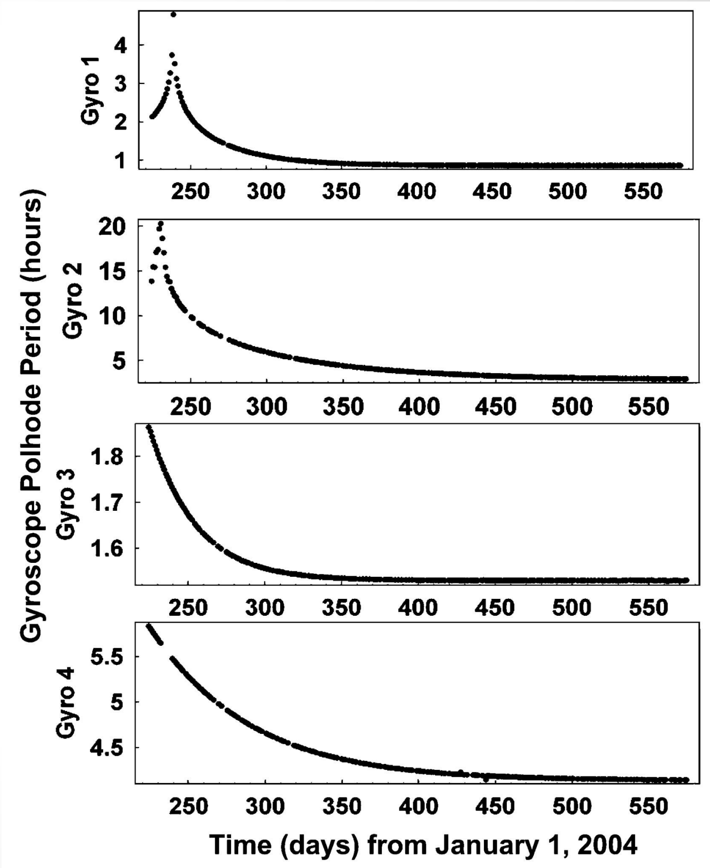


Gravity Probe B Payload Components

Science and the operations

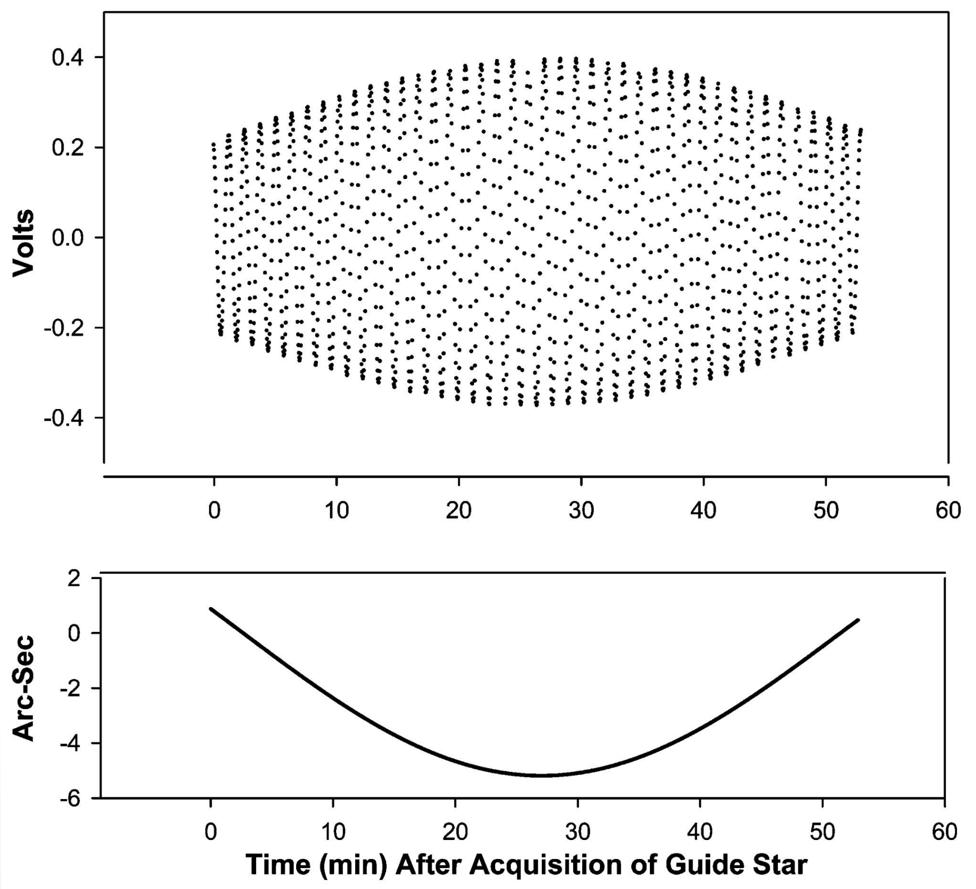
Starting trouble-The axis has too much polhode period

- The first few weeks of operation from Aug 28 to Sept 03 2004 showed that the polhode period was not as predicted and was changing.
- What should be a simple power law shows a "cusp" in the figure.
- This changing polhode path will not affect the readout or the London moment which detects the orientation of the gyroscope but it will change the contribution of trapped magnetic flux tot he total gyroscope readout signal.
- Other anomalies such as cosmic ray hits resulting in some data outage were also noted but strangely no counter measure seems to have been conducted.



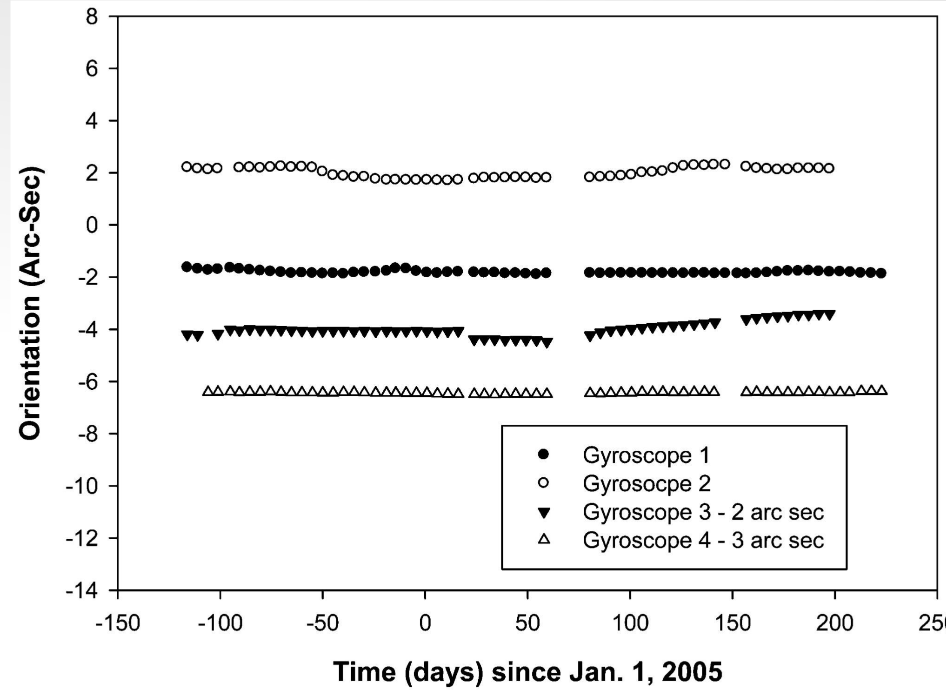
The gory details of telescope and gyroscope reading

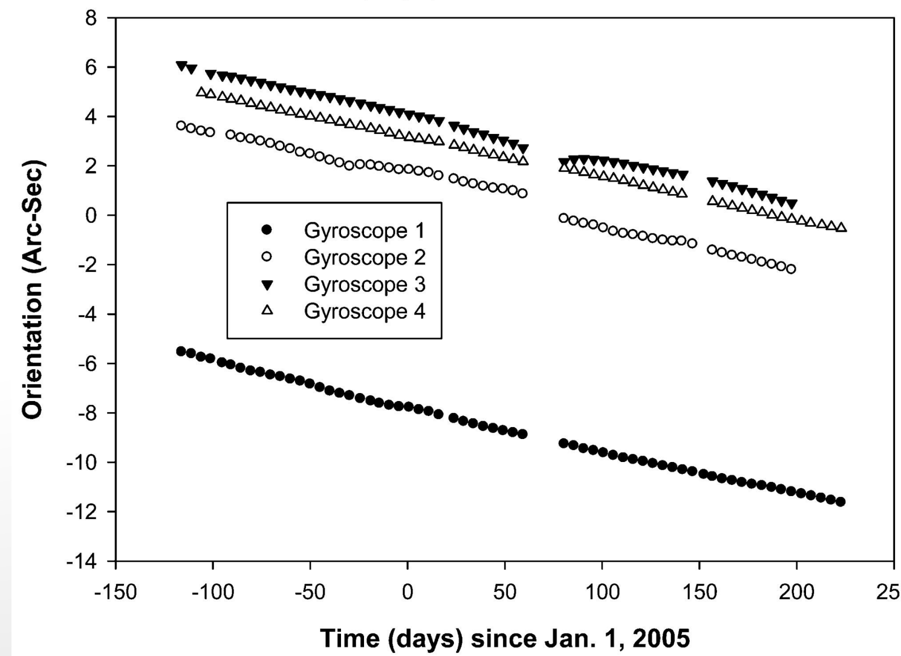
- The gyroscopes are calibrated precisely at the beginning of the mission but because of the preciseness in the calibration a dither was introduced,deliberately, of 60 mas,with a period of 34 seconds on the y-axis and an amplitude of 60 mas for 29 seconds in the x-axis.
- By measuring the amplitudes of the gyroscope and telescope readout signals at each of these two dither frequencies,the scale factor and orientation of the telescope readouts could be determined relative to each of the gyroscope readouts.
- The upper figure is the voltage abberation due to abberation of starlight and the lower figure shows the abberation due to satellite roll about the earth



Data analysis

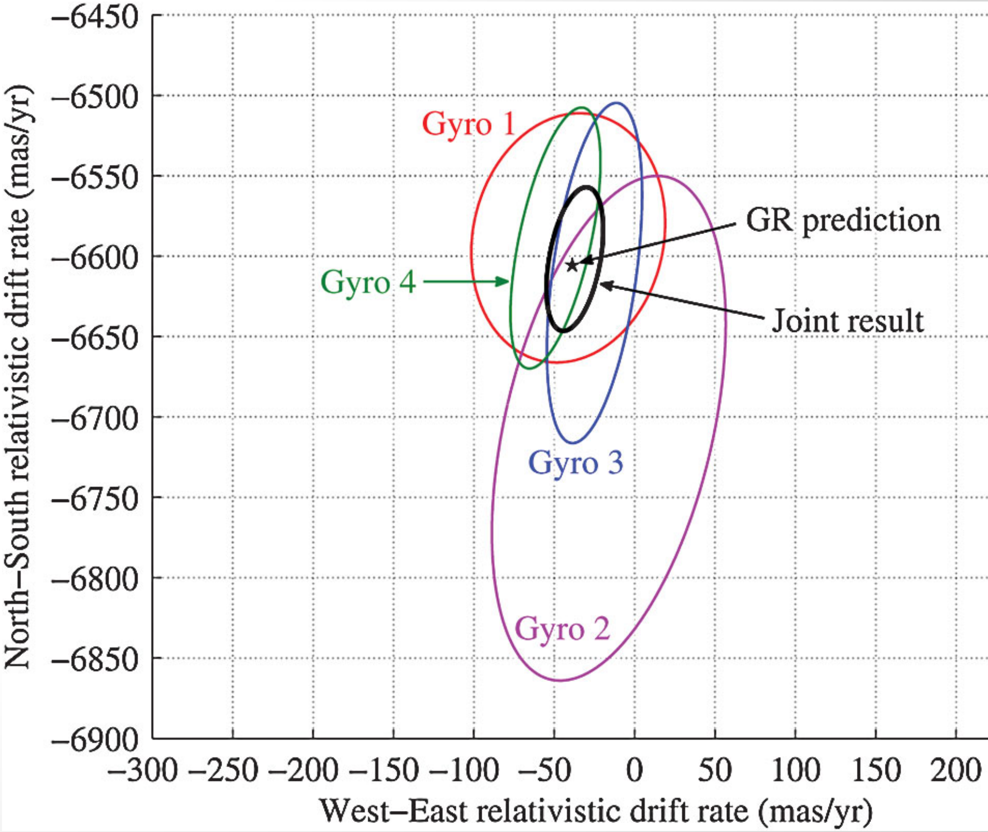
- Data analysis was done based on two techniques a) Algebraic where the gyro dynamics and measurement models were used accompanied by Newton's laws of motion to measure the geodetic effect and the frame dragging. b)Geometric which focusses on measuring the drift rate of the misalignment torque. The misalignment vector that is perpendicular to the torque is both newtonian and relativistic, but the parallel torque,when there is no roll-polhode resonance is purely relativisitc (don't ask me why!)
- The rates of drift for the algebraic method involved the calculation of misalignment drift rates, the polhode dependent torque coefficient and the unit vector along space craft roll axis
- The data was collected over 11 months with minor calibration phases, an outage because of the South Atlantic anamoly etc





Conclusions and results

- The 4 gyroscope signals were analyzed independently and the results for each gyroscope should independently confirm frame dragging in the E-W direction and the geodetic effect in the N-S direction
- The N-S geodetic drift was -6,601.8±18.3 mas/yr and the E-W frame dragging was -37.2±7.2 mas/yr. The theoretical predictions were -6,606.1 mas/yr and -39.2 mas/yr.
- The original experiiment was planned to have an accuracy of greater than 1 %, but the results were about 20% accuracy and this is primarily due to the damping of the polhode frequency according to Will(2009)



Thank you

Questions?

Additional slides-Calibration phases

- Phase 0 calibrations: In this stage a preliminary set of low risk calibration procedures were undertaken such as calibrating the SQUID readout system by changing the bias, frequency amplitude etc.
- Phase 1 calibrations: is a group of operations which were expected to significantly increase on the classical torques acting on the gyroscopes. These operations included increasing the average voltages on the electrostatic suspension system, deliberately modulating these increased preload voltages atthe satellite roll frequency, changing the position of the gyroscope within the housing,and deliberately modulating the position of the gyroscope at the satellite roll frequency.Since these operations could be performed on individual gyroscopes, they were startedon July 18, 2005, on gyroscopes 2 and 3, while gyroscopes 1 and 4 were undisturbed.
- Phase 2 calibration: These were a little more adventurous in that they involved operations on the whole space craft, rather than just the systems. These included accelerating the space craft to 10^-7g to test the capability of the thrusters to determine gyroscope torques proportional to the residual acceleration. Spacecraft orientations were changed to determine the limits to gyroscope torques