# JPL'S GALILEO Spacecraft WILL SHOOT AN INTERPLANETARY "BULL'S EYE"

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Six weeks ago JPL's Galileo spacecraft, on its way to Jupiter for a December 7 rendezvous with that gas giant, shot an interplanetary "bull's eye" when it released its probe to conduct history's first sampling of Jupiter's atmosphere. Right now, both the spacecraft and the probe are flying toward Jupiter at 30,000 miles per hour (mph). On December 7 the probe will slam into Jupiter's hydrogen-helium atmosphere at 100,000 mph as the spacecraft flies overhead and receives and records the probe's data on the structure and composition of the planet's atmosphere and clouds. The spacecraft will then fire its retrorockets to slow itself down so that it can be caught by Jupiter's gravity to conduct a two-year orbiting survey of the planet and its moons. These studies will be the culmination of a six-year, 2.4 billion mile Odyssey that began on October 18, 1989 when Galileo was launched toward Venus aboard the space shuttle Atlantis, and which included three energy boosts from the gravitational fields of Venus and Earth.

Galileo and its probe had to aim for exactly the right spots at Jupiter or the spacecraft and probe could be destroyed by hitting the planet, or they could fly right past it. This small target of about 100 miles in size is equivalent to hitting a three-cushion billiard shot so that the ball reaches the pocket with an accuracy of six millionths of an inch (two one-thousandths the width of a human hair), or pitching a strike in Dodger stadium from Atlanta with ricochets off backstops in Boston, Houston and Chicago). Since Jupiter is moving, a more appropriate analogy might be trying to hit an evasive flying duck at 25 yards with an accuracy of one one-hundredth the width of a human hair, in shifting winds.

Galileo is a follow-on to the very successful Voyager missions of the 1980s which flew by the four gaseous outer planets: Jupiter in 1979, Saturn in 1981, Uranus in 1986 and Neptune in 1989. But Galileo will conduct much more accurate studies of the largest planet by remaining in orbit around Jupiter for two years and by sending its probe to sample the planet's atmosphere. Galileo is an international collaboration, with 120 scientists from seven nations on its science teams. JPL designed and built the spacecraft, and Hughes built the atmospheric probe for NASA's Ames Research Center. Germany provided the propulsion system and two instruments. Shortly after launch the spacecraft suffered-a major failure when its high-gain radio antenna failed to unfold. While part of the operations team tried to determine the cause of the failure and send corrective commands to shock the antenna into unfurling (unsuccessfully), another group spent the intervening five years completely redesigning the science data gathering process so that it can be conducted with the spacecraft's low-gain antennas.

But how do JPL's navigators know where Galeleo is, and how fast it's going in what direction, so that they can command it to fly by Venus or Earth at just the right place and time to hit a small target at Jupiter? In a process that has been improved dramatically over the last three decades, navigators: (1) use radio signals from the spacecraft and radio emitting stars to develop very precise mathematical models of where the spacecraft is and where it's heading, of where the target planet is, and of the locations of JPL's Deep Space Network (DSN) stations in California, Spain and Australia. (2) Based on these models, they predict where the spacecraft should be at a later time. (3) They compare actual observations with the models, and, if the fit between observation and model isn't close enough, they (4) revise the model to fit actual observations. (5) 1 f the spacecraft isn't heading toward the desired spot at a target planet based on the revised models, the engineers than command the spacecraft, using, the same Earth antennas, to turn itself in the proper direction and fire its rocket engine for a prescribed time to put itself onto the correct course.

The accuracies of measurements made with the DSN transmitters, receivers and antennas must be very precise to enable accurate targeting of a few miles at distances of billions of miles. Earth station locations have therefore been measured to within one meter accuracy in longitude and in distance from the Earth's north-south axis, and to within ten meters in the direction parallel to that north-south axis. The locations of planets are known to two miles accuracy for every ten million miles distance, which translates to pointing at them with an accuracy often one-millionths of a degree. Clocks, which make use of very regular natural oscillations of atoms, must be accurate to within a billionth of a second.

All these accurate measurements are then used in several ways to determine the location, speed, and direction of travel of Galileo or other spacecraft. First, the distance to the spacecraft is determined by measuring how long it takes a radio signal to travel from Earth to the spacecraft, be turned around in the spacecraft's receiver-transmitter, and ret urned to Earth. The speed of light (and of a radio signal--including corrections for water vapor and charged particles in Earth's atmosphere) is known very precisely at 186,000 miles per second, so it is just a matter of measuring the signal timing very accurately to get the distance to the spacecraft.

The angle to the spacecraft is measured using some or all of four different techniques, depending on circumstances. The first method uses the Doppler effect--the same phenomenon that causes a car's horn or train's whistle to sound higher in pitch as it approaches, and lower in pitch as it recedes. In the case of interplanetary spacecraft, it is the rotation of Earth that causes the "pitch" (the frequency of the spacecraft's radio signal: usually between two billion and ten billion cycles per second or between two gigahertz and ten gigahertz) to be slightly higher as the Earth rotates toward the spacecraft and lower as it turns away from the spacecraft. The Doppler technique can locate a spacecraft to within ten millionths of a degree in both the longitude and latitude directions except when it is in a direction near Earth's equator, when a slightly less accurate method, called "differenced two-station ranging," is used. In this method, which can provide direction accuracy to fifty millionths of a degree, the distances to the spacecraft (measured by the time it takes the radio signal to travel between the spacecraft and Earth) as seen from two different ground stations at widely different latitudes are subtracted, and geometric calculations can then yield the angle to the spacecraft. In the case of JPL's DSN, stations in the northern hemisphere (in California or Spain) and southern hemisphere (in Australia) are separated by seventy degrees of latitude, so they provide the necessary latitude separation.

A third technique with an imposing name, which is essential to get the accuracy needed to target Galileo's atmospheric probe, is called "difference very long baseline interferometry." In this method, many error sources are eliminated and the spacecraft's direction can be estimated to within three millionths of a degree. To accomplish this, the time difference between spacecraft radio signals received at two sidely-separated ground stations is found, as well as the time difference between the received signals at the same two ground stations from a radio source at an (effectively) infinite distance (for instance, the signal from a quasar radio galaxy several billion trillion miles distant--or over a trillion times more distant than Jupiter). The difference between these two differences is then computed, and geometric calculations then yield the angle to the spacecraft. This technique is so accurate because the signals from the spacecraft and quasar travel through the same media, so that error sources are the same and are therefore subtracted out.

Although the fourth technique--optical navigation--is accurate to only 300 millionths of a degree (as compared to the one hundred-times-greater accuracy of differenced very long baseline interferometry), it is much more precise when used when the spacecraft is just in the neighborhood of a target planet or moon where the distances are much smaller than from Earth to the planet. Here, television pictures of the target object are taken against the background of known stars. From the geometry of the object and the stars, ground computers then use the rough estimates of angular position derived from the radio navigation techniques above to refine the estimate to even greater accuracy for spacecraft close to the target. This permits navigation to an even smaller "bull's eye" --the twenty mile accuracy required for making eleven orbits past Jupiter's moons.

All of this labor- and computer-intensive work will come to fruition three months from now when Galileo flies by Jupiter recording the data on the planet's atmosphere from its probe deep within Jupiter's clouds. Even with a broken high-gain antenna, Galileo should provide significant new data to help JPL, NASA, university, and foreign scientists understand the workings of the sun's largest planet.