Telescope Pointing for GOPEX

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In order for photons emitted by the GOPEX lasers to be detected by Galileo's camera, the telescopes at Table Mountain Observatory and Starfire Optical Range had to be pointed in the right direction within a tolerance less than the beam divergence. At both sites nearby stars were used as pointing references. The technical challenge was to ensure that the transmission direction and the star positions were specified in exactly the same coordinate system; given this assurance, neither the uncertainty in the star catalog positions nor the difficulty in offset pointing was expected to exceed the pointing error budget. The correctness of the pointing scheme was verified by the success of GOPEX.

I. Introduction

The GOPEX experiment [1] depended critically upon accurate pointing of the transmitting telescopes at Table Mountain Observatory (TMO) and Starfire Optical Range (SOR), for if a telescope had been pointed in the wrong direction, its laser emission would not have reached Galileo. Accurate pointing requires accurate spacecraft and transmitter ephemerides, correct algorithms for calculating the transmission direction, and reliable procedures at the telescope to point in the desired direction. The desired accuracy was determined by the beam divergence of the lasers (minimum 60 μrad or 12 arcsec) and atmospheric seeing (several arcsec); the GOPEX project assigned an error budget of 5 arcsec for pointing.

Tests of the TMO 24-in. (0.61-m) telescope mount, both hardware and software, indicated that one could not point at an arbitrary direction in the sky without introducing errors larger than GOPEX's tolerance. The causes of this error remain unknown; possible explanations include unmodeled mount misalignment, flexure, or mismodeled atmospheric refraction. Whatever its source, the absolute pointing error ruled out using absolute pointing.

Relative pointing, however, proved much more reliable. One can point the telescope at one star and then offset to another nearby star with an error of only a few arcseconds, provided that the two stars are separated by less than one or two degrees. This behavior suggested that the best way to point the telescope for GOPEX was to point first at a star close to Galileo, then to move from the star to Galileo. Therefore, GOPEX required a catalog of suitable reference stars surrounding Galileo's position during the experiment.

The remaining sections of this article present in detail the various aspects of the pointing problem: predictions of the uplink direction, the actual pointing of the telescopes, and the development of the reference star catalog.

II. Pointing Prediction

The "raw material" for predicting pointing consists of a planetary ephemeris file, a spacecraft ephemeris file (known as a P-file), the Earth-fixed coordinates of the telescope, and the Earth orientation model. Updated P-files were received just prior to the first day of the experiment

and again after three days; each contained more tracking data and was, therefore, more precise than its predecessor.

The coordinates for the uplink direction were found as follows:

(1) A P-file was received from the Galileo Navigation Team and converted, using the standard navigation utility program PVTOEXP, from the B1950 coordinate system to the J2000 coordinate system. Since a P-file by construction uses an inertial reference frame, this transformation is accomplished by a simple 3 × 3 rotation matrix applied to both positions and velocities.

(2) The position of Galileo at the midpoint of each Solid-State Imaging (SSI) camera exposure was found relative to the barycenter of the Solar System by interpolating and adding vectors from the P-file and from the DE202 planetary ephemeris.

(3) The position of the telescope, also relative to the Solar System barycenter, was similarly found at the midpoint of the *transmission* window. The one-way light time, and therefore the position, were determined iteratively. The Earth was oriented using the J2000 precession model [2], nutation angles from the DE202 planetary ephemeris, and timing and polar motion angles from the P-file. For GOPEX, the light time amounted to just over two seconds on the first day and about 20 seconds on the last day.

(4) The difference between the above two vectors gives the *true* direction referred to the J2000 system. The *transmission* direction is derived from this by removing the effect of classical stellar aberration: one subtracts v/c from the true unit vector, where v is the Solar System barycentric velocity of the telescope and c is the speed of light. This correction accounts for the fact that the outgoing photons are displaced forward by the transmitter's velocity, as seen by an observer at the Solar System barycenter. For GOPEX, since Galileo's motion was almost exactly radially outward relative to the Earth, the effects of light time and aberration almost exactly cancel. This happy situation will not always hold, however, so both effects were included in the software.

(5) The transmission vector just found is in *apparent* coordinates in the J2000 system. The *mean* position of a star as given in a catalog, however, is the direction from which an observer at the Solar System barycenter would observe the starlight. Any other observer would see the starlight emanating from a different direction, the *apparent* direction, due again to stellar aberration. One must, therefore, either compute the apparent coordinates of the reference stars or else transform the transmission direction to match the mean positions of the stars. The latter option, to produce *astrographic* coordinates, was chosen for the sake of simplicity, to avoid having the star coordinates change as the telescope's velocity changes. One therefore subtracts v/c again from the unit vector; this reverses the change in position from astrographic to apparent due to the motion of the observer.

(6) The telescope mount is nominally aligned with the true north pole of date. In order that computed offset directions may match those commanded to the telescope, one precesses [2] the above vector into *mean-of-date* coordinates with the epoch chosen to be the midpoint of the GOPEX experiment. Choosing a fixed epoch again keeps the star positions constant over time while having a negligible effect on the direction to celestial north.

The above procedure, performed for every transmission, resulted in a file of transmission directions that were in the same coordinate system as the star catalog. A plot of the transmission directions for TMO appears in Fig. 1. The longest line represents the first day of the GOPEX experiment.

Pointing predictions using the above algorithm were also produced for SOR but not used there, as SOR had its own prediction capability. SOR's geocentric algorithm included the following steps:

(1) JPL provided SOR with a list of positions and velocities of Galileo relative to the Earth, referred to J2000 coordinates, at the midpoint of each SSI exposure. The vectors were interpolated directly from the geocentric P-file.

(2) SOR rotated each vector into Earth-fixed true-of-date coordinates by applying precession, nutation, and sidereal time matrices, these angles being computed for the uplink time.

(3) The direction from SOR to Galileo was found in true-of-date coordinates by vector subtraction. This was taken to be the transmission direction.

This algorithm, while not rigorously correct, gave answers that agreed with JPL's predictions to within a fraction of an arcsecond. Using a different algorithm at each site helped to guard against error at one site or the other.

III. Telescope Pointing

A. Procedure at TMO

The TMO telescope control program includes a "retrieve" command to point the telescope at coordinates which appear in a file of positions. Both the uplink directions and the coordinates of the reference stars were produced at JPL in the format used at TMO, and the files were transmitted electronically to TMO for use at the telescope. However, the retrieve command did not work properly during checkout, so all pointing commands were issued manually by typing in the coordinates. Having constant star coordinates proved to be a wise decision.

During the experiment, the pointing engineer would first command the telescope to the chosen reference star, one that was northwest of the transmission direction, visible through the eyepiece, and as close to Galileo as possible. The reference stars actually used are listed in Table 1. Once the star was centered, the telescope right ascension and declination were reset to match the star's catalogued coordinates, thus calibrating the pointing, and the telescope was then offset to the predicted transmission direction. A second command to point anew at the transmission direction was issued just before each transmission, in order to eliminate any accumulated tracking errors. Selecting a star northwest of Galileo helped to combat the effect of atmospheric refraction: The star during calibration would appear at nearly the same altitude as Galileo would have during uplink, and so both would be affected nearly equally by refraction.

B. Procedure at SOR

SOR also pointed its telescope by offsetting from a nearby reference star. The SOR mount is much more stable than TMO's, and modeled better, so that it did not need to return to the reference star and recalibrate before every transmission. Rather, after the initial acquisition of the reference star, the telescope would move from one transmission direction to the next. Occasionally, the reference star would be observed as a check, but no recalibration was ever required.

IV. Star Catalog Development

The characteristics of the TMO telescope mount dictated that the reference stars be as close as possible in the sky to Galileo. This in turn meant that the reference catalog needed to be fairly dense, including many dim stars, in order to assure the availability of a suitable star every night. However, the stars also had to be bright enough to be seen visually through TMO's telescope at the coudé focus. The GOPEX project thus required a catalog of all stars brighter than magnitude 12.0 within a 5- by 5-deg region surrounding the uplink direction.

Existing star catalogs generally fall into two categories: very precise but sparse, and less precise but more complete. The *Fifth Fundamental Catalogue* (FK5) [3], with 1535 stars over the whole sky and precisions of several hundredths of an arcsecond, is an example of the former; the *Astrographic Catalogue Reference Stars* (ACRS) catalog [4], with 300,000 stars and precisions of half an arcsecond, is the most recent example of the latter. Furthermore, many star catalogs, particularly photographic ones, such as the ACRS, have a *maximum* brightness as well as a minimum brightness, as too-bright stars are overexposed and do not yield reliable image centroids.

Three catalogs were used to construct the GOPEX star catalog, in decreasing order of preference:

(1) The ACRS supplied 112 stars, most of which were between seventh and tenth magnitude.

(2) *The Smithsonian Astrophysical Observatory (SAO) Star Catalog* [5] supplied three stars: two that were too bright for the ACRS, and one that was the secondary component of a double star system.

(3) *The Hubble Guide Star Catalog (GSC)* [6–8] supplied 260 stars that were too faint for the ACRS.

There were no FK5 stars in the region of interest.

A comparison of ACRS and GSC coordinates for stars that appeared in both catalogs revealed no statistically significant differences between the coordinate systems of the two catalogs over the GOPEX region. This check was important because the GSC is known to have occasional large systematic biases. The final merged catalog, referred to J2000 coordinates, is believed to be accurate to half an arc second, well below the error budget.

The GOPEX star catalog was precessed to mean coordinates at epoch 1992 December 12 for use at TMO. In this way the stars' coordinates were in the same system as the uplink directions, so that one could offset the telescope from a star to Galileo without having to perform any calculations at the telescope.

The original J2000 version was transmitted to SOR, where the catalog was transformed into true-of-date positions in order to match their own uplink predictions which were likewise expressed in true-of-date coordinates.

V. Conclusion

All the components of telescope pointing for GOPEX, from the construction of a star catalog and prediction algorithms to the procedures at the telescopes at TMO and SOR, were spectacularly validated when the first long exposures taken by Galileo showed that laser light from both sources had reached the spacecraft. Even on the final days of the experiment, when the beam divergence at TMO was reduced to 60 μrad, the consistent uplink successes confirmed the accuracy of the telescope pointing strategy.

References

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[8] H. Jenkner, B. M. Lasker, C. R. Sturch, B. J. McLean, M. M. Shara, and J. L. Russell, "The Guide Star Catalog. III. Production, Database Organization, and Population Statistics," *Astron. J.*, vol. 99, no. 6, pp. 2082–2154, June 1990.

Table 1. GOPEX Reference Stars Used at TMF

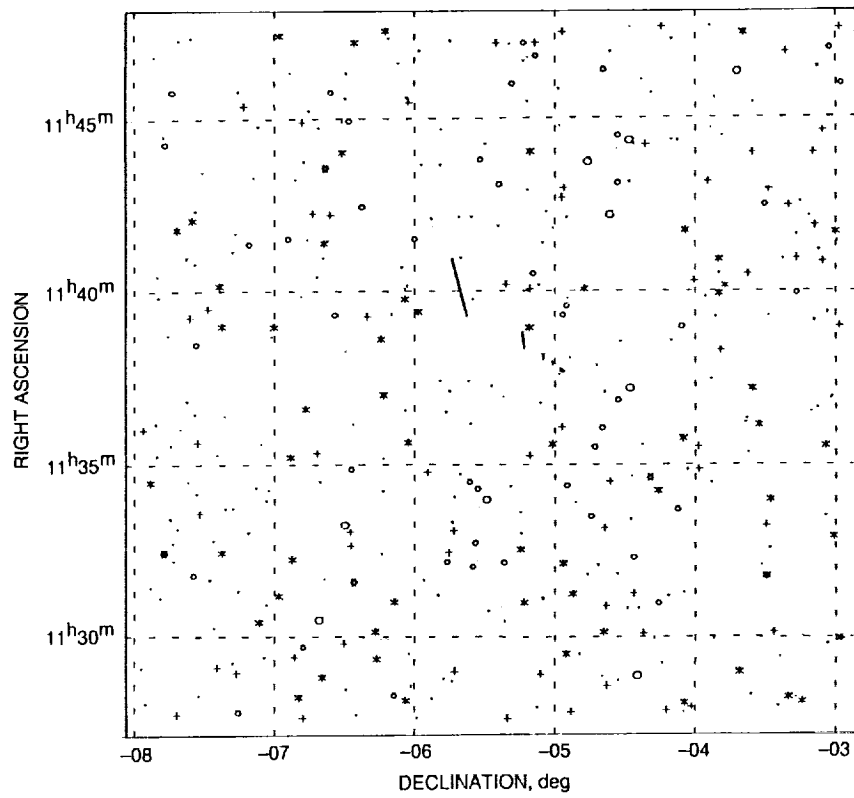| Date Dec., 1992	Transmissions	Right Ascension h min sec	Declination deg arcmin arcsec	Magnitude
09	1 to 50	11 40 11.4	−5 21 02	10.35
09	51 to 52	11 40 29.9	−5 09 34	8.02
10	All	11 38 55.1	−5 11 03	9.45
10	1 to 6	11 39 18.2	−4 56 43	8.77
11	7 to 8	11 34 37.3	−4 19 20	6.39
11	9 to 20	11 39 18.2	−4 56 43	8.77
12	All	11 36 51.1	−4 33 12	8.39
14	All	11 36 51.1	−4 33 12	8.39
15	All	11 36 51.1	−4 33 12	8.39
16	All	11 36 51.1	−4 33 12	8.39

Fig. 1. The uplink direction from TMF to Galileo plotted against the GOPEX star catalog. Galileo's apparent motion was east to west (left to right) daily with a slow northern drift; the longest line corresponds to the first day of the GOPEX experiment. Stars are plotted by magnitude: five- and six-pointed stars for magnitudes 5 and 6; large and small open circles for magnitudes 7 and 8; asterisks for magnitude 9; plus signs for magnitude 10; dots for magnitude 11. Coordinates are referred to the mean equinox and equator of December 12, 1992.

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