Selection and Observability Tests of GOPEX Reference Stars

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Reference stars that can be used for calibration of telescope pointing in the GOPEX (Galileo OPtical communications with an Earth-based Xmitter) deep-space optical communications demonstration are selected. Observations of similar stars were conducted to test how easily the reference stars will be observed under the conditions to be encountered during GOPEX. It is concluded that the planned technique of observing the stars by eye through the telescope may not be adequate, and some alternative strategies are suggested.

I. Introduction

In the Galileo optical communications with an Earth-based transmitter (GOPEX) demonstration [1], a laser signal will be transmitted from the 24-inch telescope at JPL's Table Mountain Observatory (TMO) to Galileo after its Earth flyby in December 1990, and again around the second Earth gravity assist in December 1992. The solid-state imaging camera on the spacecraft will be used as the receiver-detector for this test of optical communications.

One of the challenges of this work is in the accurate pointing of the laser. The spacecraft will be far too dim to be visible in the optical from TMO, so the position, as determined by standard rf navigation techniques, will be provided to the GOPEX team at TMO, and the telescope will be blind pointed. The pointing accuracy needed is about 10 μrad. Atmospheric refraction models may have errors several times that amount, and flexure-induced errors in the telescope may be nearly that large. To correct for these error sources, the demonstration plan includes pointing the telescope at a nearby reference star to make a local correction to the pointing. Since the positions of most stars are known to better than 3 μrad, this will allow the telescope's pointing to be calibrated in a part of the sky near that used for GOPEX.

Orbital mechanics and Galileo Project scheduling limit the demonstration to several days on which Galileo rises at about 0510 PST, so by the time it is well above the horizon, the sky will be brightening from the Sun. The availability of reference stars then may be limited. To determine whether nearby stars might be visible at the time of the demonstration, stars were observed at TMO in the morning skies, and the viewing conditions were compared with those expected for December 1990.

II. GOPEX Reference Stars

The position of Galileo will not change significantly during the GOPEX window, so December 10, 1990 is used as a representative date. Galileo's position is predicted to be near 14 hr 40 min right ascension and -33 deg 45 min declination during the GOPEX window. Locating this position on a star chart (Fig. 1), from [2], reveals two nearby bright stars, which may be identified from an atlas [3] as shown in Table 1. The positions listed have been corrected for precession and proper motion to bring them to the December 10, 1990 epoch. In the table, the visual magnitude is given by m, and B–V is the observed color index (sometimes known simply as color), measured as a stellar magnitude. This latter number is a measure of the difference of the apparent stellar brightness at B (435 nm) and at V (555 nm). Therefore, it describes how blue the star appears. Smaller B–V values correspond to bluer stars. The typical range is from about 0.4 for a very blue star such as α Virginis (Spica) to nearly 2.0 for the red giant α Orionis (Betelgeuse). The Sun is 0.62, and the white star α Lyrae (Vega) is 0.00.

The color of the star is important because the team will try to observe it against the blue sky. Therefore, a red star may be observable with appropriate filtering more easily than a blue star. Of course, the spectral response of the detector (whether eye or electronic device) must be considered. In addition, the laser will transmit at 532 nm or 1064 nm, so it will be important to evaluate the errors introduced in measuring the atmospheric index of refraction at one wavelength and transmitting the laser signal at another. Nevertheless, this article addresses only the question of observing a star in the vicinity of Galileo. Because Gstar1 is brighter, redder (thus providing better contrast), and closer to Galileo than Gstar2, it is considered to be the prime reference star.

Now it is necessary to determine how far this reference star is from the Sun and from Galileo. On December 10, 1990, the Sun will be at 17 hr 6 min and −22 deg 52 min [4], and on that date the following angular separations will be observed:

Galileo – Sun	33.8°
Galileo – Gstar1	1.6°
Sun – Gstar1	32.7°

Using an equation found in [4], the rising time of any celestial coordinates can be calculated. From that calculation and tables in [4], it is determined that on December 10:

Galileo rises	0510 PST
Astronomical twilight begins	0527 PST
Sunrise	0657 PST

III. Test Observations

To estimate the observability of the reference stars against the blue sky, members of the GOPEX team tried to observe similar stars through the 24-inch telescope at TMO on three mornings in July 1990. All observations were visual, as the plan proposed by the TMO Resident Astronomer was to use visual observations for GOPEX. Stars were selected that covered a range of angular distances from the Sun, including the value to be encountered in December. Most of the stars are close to Gstar1 in visual magnitude. Table 2 is a summary of the observations, listed from maximum solar elongation (σ) to minimum.

The seeing was particularly poor on 7/24 ($\approx$ 10 arcsec), so the stars were harder to see than on good days. Of course, there is no guarantee of good seeing in December. Indeed, a wide range of sky conditions is possible then. The team should be prepared to operate under as many conditions as possible that do not preclude the transmission of the laser light through the atmosphere.

Based on the distance from the Sun and the visual magnitude, the best comparisons from the data in Table 2 with the Galileo reference star, Gstar1, are shown in Table 3.

Comparing the sky radiance of the high summer sky with that of the low winter sky will require predictions using the computer code LOWTRAN7 [5]. Until these predictions (which are in progress) are available, a direct comparison of the winter date with the summer dates shown in Table 4 is used.

From the above comparisons it is concluded that the reference star is likely not to be visible shortly after sunrise, or within 2 hours after the beginning of twilight. In either case, Gstar1 probably will be impossible to see by 0730 PST on December 10.

Because of this conclusion, the next brighter star in the vicinity of Galileo has been identified. The nearest star brighter than Gstar1 is θ Centauri, with:

$$m = 2.06$$

$$\sigma = 40.8°$$

$$B\text{–}V = 1.01$$

Since it is more than 40 deg from the Sun, it can be seen longer, but it will be 7.2 deg from Galileo on December 10. This is probably too far to be of value, but that will have to be evaluated more carefully with the use of atmospheric refraction models and tests of the telescope flexure after the TMO upgrades (currently in progress) are completed in September. Pointing tests with stars separated by this angle may be undertaken to determine whether the required accuracy can be achieved.

IV. Alternative Approaches

It may be that the difference in sky brightness will not make a significant difference in the observability of the reference star. Even if the winter sky allows Gstar1 to be observed for some time longer, it is unlikely that it will remain visible for many hours longer, and the demonstration is planned for the period of time Galileo is above the horizon (it will set at approximately 1320 PST).

There are alternatives to the simple approach described here for observing the star against the background sky. The use of filters to take advantage of the spectral difference between the blue sky and the red Gstar1 may enhance the observability. A filter that cuts off below the red may allow enough starlight to pass that it will raise the contrast without lowering the intensity too much.

A further modification, which would be done in conjunction with the filter, is to use a charge-coupled device (CCD). The field of view per pixel can be very small with the CCD, so it may allow the detector to locate the star with less interference from the spatially extended blue sky than the eye experiences.

It is planned that, following further analysis, if these options are deemed appropriate, they will be tested at TMO. A series of tests is planned from September through November with the laser and telescope at TMO. There will be ample opportunity to explore these alternative strategies for locating the reference star.

V. Conclusion

A reference star near Galileo's position at the time of the GOPEX demonstration has been identified. Based on tests with stars of similar visual magnitude, color index, and angular distance from the Sun, it is likely that the originally intended technique for correcting for atmospheric refraction and telescope flexure cannot be accomplished. It is planned that other techniques will be analyzed and tested as appropriate during the coming months to prepare for the December 1990 flyby.

Acknowledgments

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References

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Table 1. Identification of stars near Galileo's location on December 10, 1990

Designation	R.A.	Declination	m	B–V	Name
HD129456	14h 43m 20s	$-35° 08' 04''$	4.05	1.35	Gstar1
HD129685	14h 44m 40s	$-35° 09' 15''$	4.92	0.01	Gstar2

Table 2. Visual observations of stars through 24-inch telescope at Table Mountain Observatory

Star	m	σ, deg	B–V	Date	Time, PDT	Observation
α UMi	2.02	67.6	0.60	7/11	1153	Moderate
88 Tau	4.25	53.0	0.18	7/24	0517	Moderate
o^2 Ori	4.07	47.3	1.15	7/24	0520	Easy
16 Ori	5.43	45.3	0.24	7/24	0520	Moderate
ζ Ori	1.77	43.2	−0.21	7/24	0540	Moderate
					0556	Moderate
					0600	Moderate
					0624	Moderate
					0638	Difficult
					0650	Difficult
γ Ori	1.64	42.9	−0.22	7/24	0522	Easy
α Leo	1.35	41.2	−0.11	7/11	1130	Not visible
88 Tau	4.25	40.3	0.18	7/10	0425	Moderate
					0510	Moderate
					0613	Not visible
ϕ^1 Ori	4.41	39.5	−0.18	7/24	0524	Easy
ϵ Tau	3.54	39.3	1.02	7/10	0500	Moderate
λ Ori	3.39	39.3	−0.18	7/24	0530	Easy
					0543	Moderate
					0612	Not visible
α Tau	0.85	39.1	1.54	7/11	1130	Not visible
ϕ^2 Ori	4.09	39.1	0.95	7/24	0532	Easy
					0608	Not visible
π^2 Ori	4.36	37.5	0.01	7/10	0515	Easy
ζ Tau	3.00	36.3	−0.19	7/24	0534	Easy
					0603	Difficult
					0616	Very difficult
					0636	Not visible
α Ori	0.50	35.6	1.85	7/24	0550	Easy
					0621	Easy
o^2 Ori	4.07	34.4	1.15	7/10	0520	Easy
					0545	Easy
					0555	Moderate
					0600	Not visible
					0630	Not visible
130 Tau	5.5	34.4	0.30	7/24	0548	Not visible
μ Ori	4.12	33.1	0.15	7/24	0554	Not visible
16 Ori	5.43	32.9	0.24	7/10	0520	Difficult
γ Ori	1.64	31.2	−0.22	7/10	0525	Easy
					0543	Easy
					0600	Not visible
ϕ^1 Ori	4.41	27.5	−0.16	7/10	0530	Difficult
					0540	Not visible
λ Ori	3.39	27.2	−0.18	7/10	0540	Not visible

Table 3. Comparison of Gstar1 with observations of comparable stars

Star	m	σ, deg	B–V	Date	Time, PDT	Observation
Gstar1	4.05	32.7	1.35	12/10		
o^2 Ori	4.07	34.4	1.15	7/10	0520	Easy
					0545	Easy
					0555	Moderate
					0600	Not visible
					0630	Not visible
μ Ori	4.12	33.1	0.15	7/24	0554	Not visible

Table 4. Critical times (PDT) for test observations

Date	Twilight begins	Sunrise	Disappearance of star
7/10	0409	0554	0600
7/24	0424	0603	<0554

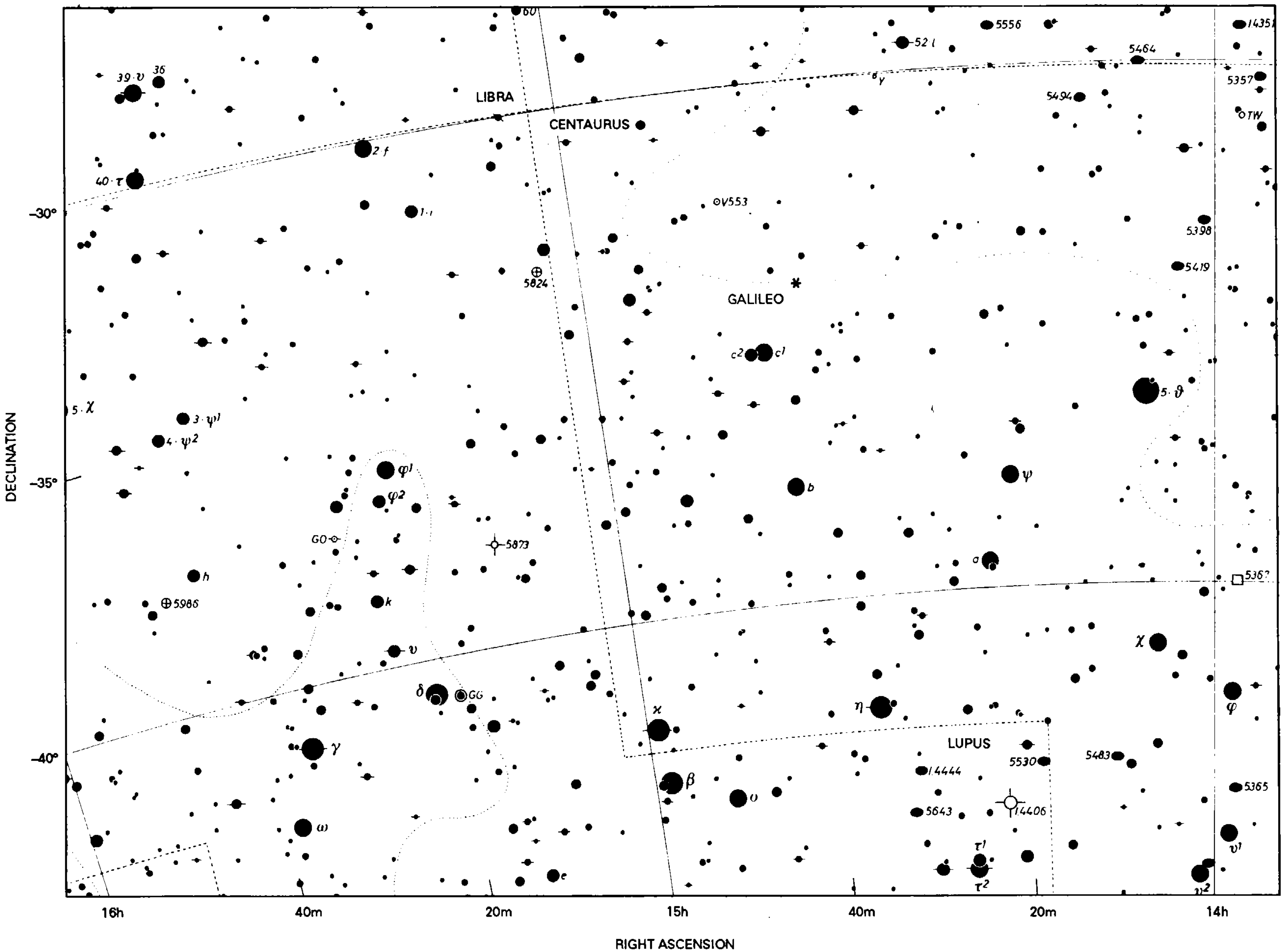

Fig. 1. Predicted location of Galileo (*) at time of the GOPEX demonstration. The nearby stars labeled c^1 and c^2 are referred to in the text as Gstar1 and Gstar2, respectively.