AAS 93-685

TRACKING GALILEO AT EARTH-2 PERIGEE USING THE TRACKING AND DATA RELAY SATELLITE SYSTEM

C. Edwards[1], J. Anderson[2], P. Beyer[3], S. Bhaskaran[4], J. Border[5],
S. DiNardo[5], W. Folkner[6], R. Haw[6], S. Nandi[5], F. Nicholson
C. Ottenhoff[7], S. Stephens[5]

The Tracking and Data Relay Satellite System (TDRSS) was successfully used to track the Galileo spacecraft on December 8, 1992, during the Galileo Earth-2 flyby. This flyby enabled Galileo to obtain a gravity-assisted energy increase as part of the Venus-Earth-Earth trajectory en route to the planet Jupiter. Due to the low perigee altitude of about 300 km, there was a gap in DSN coverage **for nearly two hours around** perigee, from 13:49-15:40 GMT. During this time, Galileo was within the field-of-view (FOV) of the spare Tracking and Data Relay Satellite (1 DRS) at 62 deg W longitude. In order to obtain a continuous Doppler arc throughout the perigee period, the TDRS was configured to observe the Galileo 2.3-GHz carrier signal with one of its S-band Single-Access (SA) antennas, and coherently relay the signal to the White Sands Ground Terminal (WSGT), where a special baseband tracking receiver was installed to enable reliable carrier phase (Doppler) extraction during the high signal dynamics at perigee. An S-band calibration signal transmitted from WSGT was simultaneously observed with the other TDRS SA antenna in order verify system performance in real time and to remove the effects of TDRS motion during the tracking, To our knowledge, this represents the first time the TDRS System has been used to track a spacecraft on a hyperbolic trajectory. The techniques used to acquire these data are described, and the perigee Doppler data are examined in the context of the fully reconstructed flyby trajectory.

INTRODUCTION

The Galileo spacecraft is in the midst of a 6-year interplanetary cruise en route to the planet Jupiter, where it will arrive in December, 1995. To achieve the required energy for

---

[1] Assistant Program Manager, TDA Technology Development, Jet Propulsion Laboratory, Pasadena, CA 91109. Senior Member AIM.

[2] Staff Scientist, Jet Propulsion Laboratory, Pasadena, CA 91109.

[3] Manager, Tracking and Data Systems, Galileo Project, Jet Propulsion Laboratory, Pasadena, CA 91109.

[4] Member of the Technical Staff, Jet Propulsion Laboratory, Pasadena, CA 91109. Member AAS.

[5] Member of the Technical Staff, Jet Propulsion Laboratory, Pasadena, CA 91109.

[6] Member of the Technical Staff, Jet Propulsion Laboratory, Pasadena, CA 91109. Member AIAA.

[7] Senior System Engineer, TRW Space and Electronics Group, Las Cruces, NM, 88004. Senior Member AIAA.

reaching Jupiter, the cruise incorporates one Venus gravity assist and two Earth gravity assists. The first Earth gravity assist (EGA 1) was on December 8, 1990, 20:34:34 UTC at a perigee altitude of about 960 km. Nearly continuous two-way Doppler and range data were collected from the Deep Space Network (DSN) from November 2 to December 13, 1990. However, there was a gap of about 1 hr 9 min around perigee, where no two-way data were collected.

Subsequent analysis of the fly-by trajectory [1] indicated an anomalous apparent velocity increase of 4 mm/s during this gap in two-way tracking coverage near perigee. That is, in order to obtain a good fit between the inbound and outbound Galileo trajectories, it was necessary to include an impulsive maneuver of about 4 mm/s along the Galileo velocity vector at perigee, While this small velocity anomaly had no significant impact on mission navigation, and did not influence the successful Earth-1 gravity assist, there was considerable interest in the project navigation and radio science teams in understanding its origin. A variety of possible sources for the velocity anomaly have been investigated by the Galileo project navigation and science teams, including mismodeling of maneuvers on the spacecraft, uncalibrated Earth propagation media effects, errors in the orbit determination software, unreported thruster firings, or even new physical phenomena, To date, however, no suitable explanation for the anomaly has been found,

Members of the Galileo science team were especially intrigued by the notion that the observed anomaly might be related to some unknown and previously unobserved physical phenomenon leading to a violation of special and/or General relativity. Indeed, the Earth fly-by represents a somewhat unique experimental scenario, with very rapid rates of change of Earth-spacecraft range and of the gravitational field at the spacecraft, As a result, the Galileo science team made a special request for continuous tracking of Galileo throughout its Earth-2 encounter perigee.

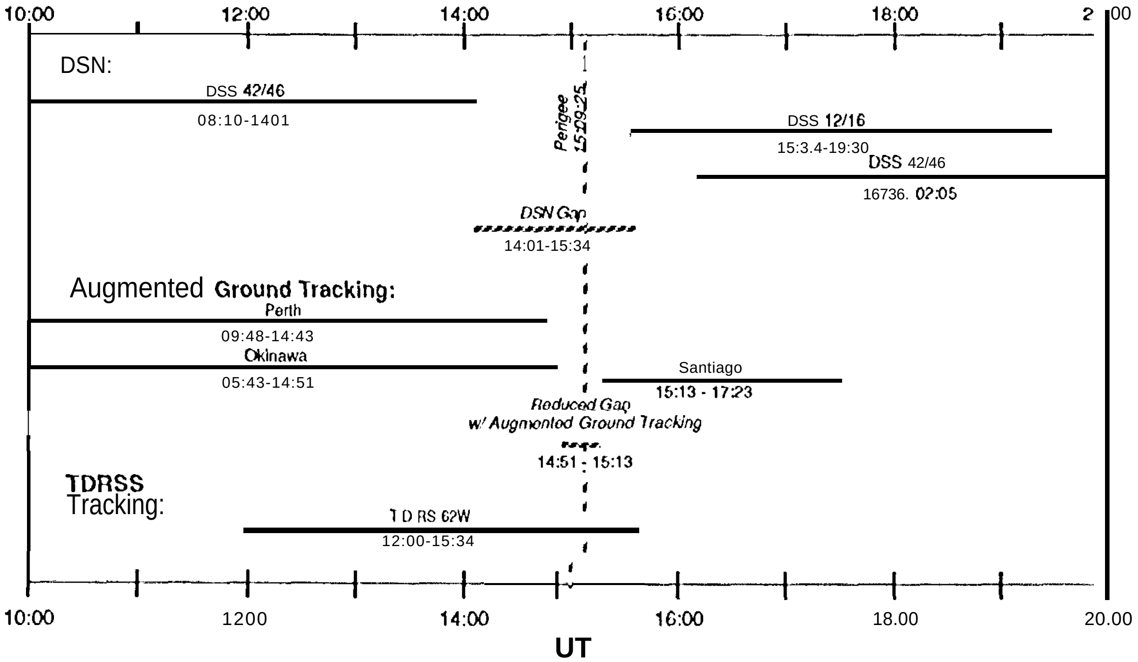


Figure 1: Galileo tracking visibility during Earth-2 flyby, showing coverage times from the Canberra and Goldstone DSN tracking complexes, from additional ground stations located at Santiago, Perth, and Okinawa, and from the TDRS-C satellite at 62 deg W longitude.

TRACKING SUPPORT FOR THE EARTH-2 FLYBY

The second Earth flyby occurred on December 8, 1992, 15:09 UTC, at a 303-km altitude over the South Atlantic. The low perigee altitude led to a gap of nearly two hours in visibility from the DSN, with a resulting gap in two-way Doppler tracking. To partially fill this visibility gap, one-way Doppler tracking was scheduled at ground stations at Santiago, Perth, and Okinawa, providing tracking coverage for all but 22 minutes around perigee [2]. To fill this remaining gap in tracking coverage at perigee, an investigation was made of the possibility of using one of the geostationary satellites in the Tracking and Data Relay Satellite System (TDRSS). At the time of the Earth-2 flyby, there were four TDRSS satellites on orbit, at longitudes of41 deg W longitude, 62 deg W longitude, 171 deg W longitude, and 174 deg W longitude. It was found that the Tracking and Data Relay Satellite (TDRS) at 62 deg W longitude, designated TDRS-C and which we will refer to here as TDRS-62W, provided the best visibility of the Galileo perigee trajectory. Figure 1 shows a visibility timeline for the ground stations and for the TDRSS. Figure 2 shows the Galileo perigee trajectory as viewed from TDRS-62W. indicated on the figure is the elliptical field-of-view (FOV) constraints for the TDRS-62W SA antennas. The addition of the TDRS-62W coverage completely fills the gap in DSN coverage, providing continuous tracking of Galileo during perigee.

GALILEO DATA ACQUISITION USING THE TDRSS

Due to the pulse code modulation/phase shift keying/phase modulation (PCM/PSK/PM) telemetry modulation scheme used by JPL deep space missions, as well as the high signal

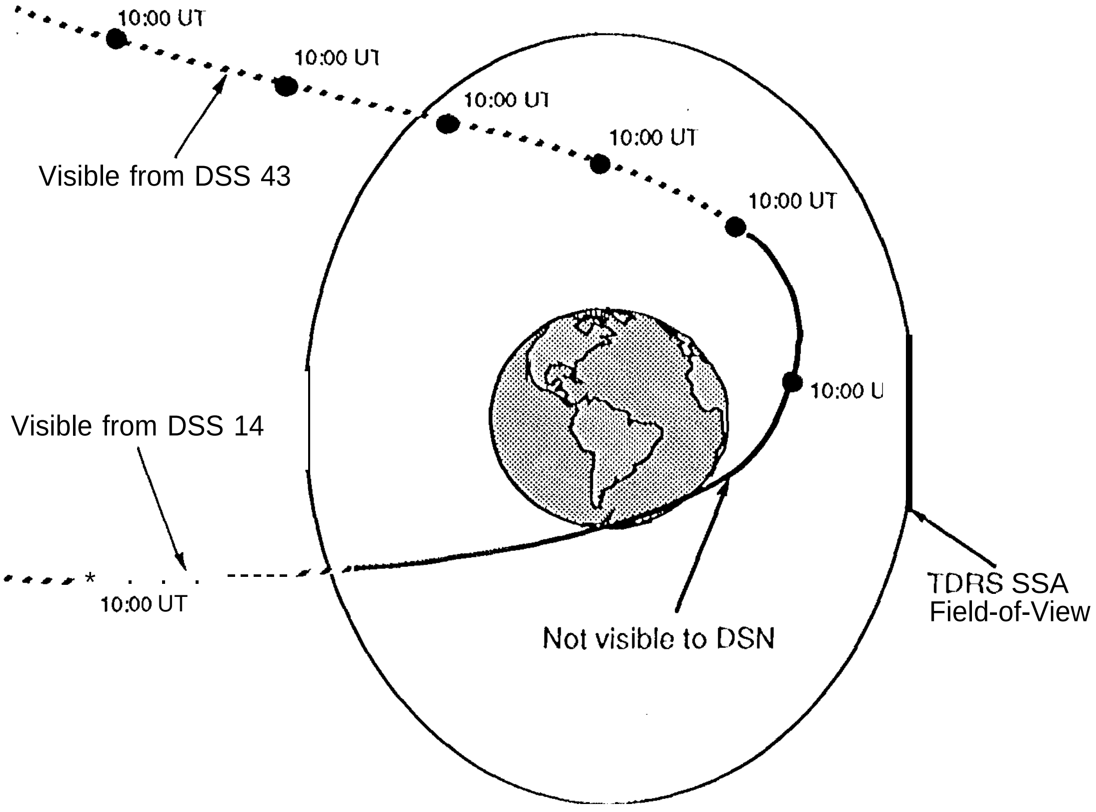


Figure 2: Galileo Earth-2 fly-by on 8-DEC-1992 as viewed from the TDRS positioned at 62 deg W longitude. The elliptical field-of-view constraints for the TDRS SA-antenna are shown.

dynamics expected at perigee, there was considerable uncertainty as to whether the nominal TDRSS tracking receiver at the White Sands Ground Terminal (WSGT) could successfully lock onto and track the Galileo carrier through perigee. Instead, it was decided to use a new digit al baseband receiver developed at JPL to perform the carrier acquisition and tracking. This receiver, which we refer to as the Experimental Tone Tracker (ETT), is derived from the Turbo-Rogue GPS tracking receiver [3] and features two IF signal inputs and up to 24 separate tone models which can be simultaneously tracked,

Figure 3 shows the configuration used to perform the Galileo tracking. One SA antenna of the TDRS-62W received the 2.3-GHz (S-band) signal transmitted from the Galileo low-gain antenna. The TDRS receives a 15. 15-GHz pilot tone from WSGT which serves as a frequency reference for the TDRS spacecraft, Based on this uplink frequency reference, the TDRS-62W generates a mixing LO to coherently translate the Galileo signal to a frequency of 13.7 GHz for transmission to WSGT. Figure 4 details the frequency scheme on board the TDRS-62W for these observations.

At WSGT, the received 13.7-GHz signal is downconverted to a 370-MHz IF frequency, which is subsequently processed by the WSGT tracking receiver. This mixing process is typically predicts-driven to remove the *a priori* expected Doppler shift from the signal. For our purposes, it was decided to have a simple fixed-frequency downconversion and handle the signal dynamics in the baseband tracking processor. We defeated the WSGT Doppler compensation by supplying a fixed-frequency mixing 1.0 to the S-band Single-Access (SSA) downconverter. We chose the frequency of this mixing 1.0 to provide a 350-MHz IF frequency, based on the signal requirements of the ETT.

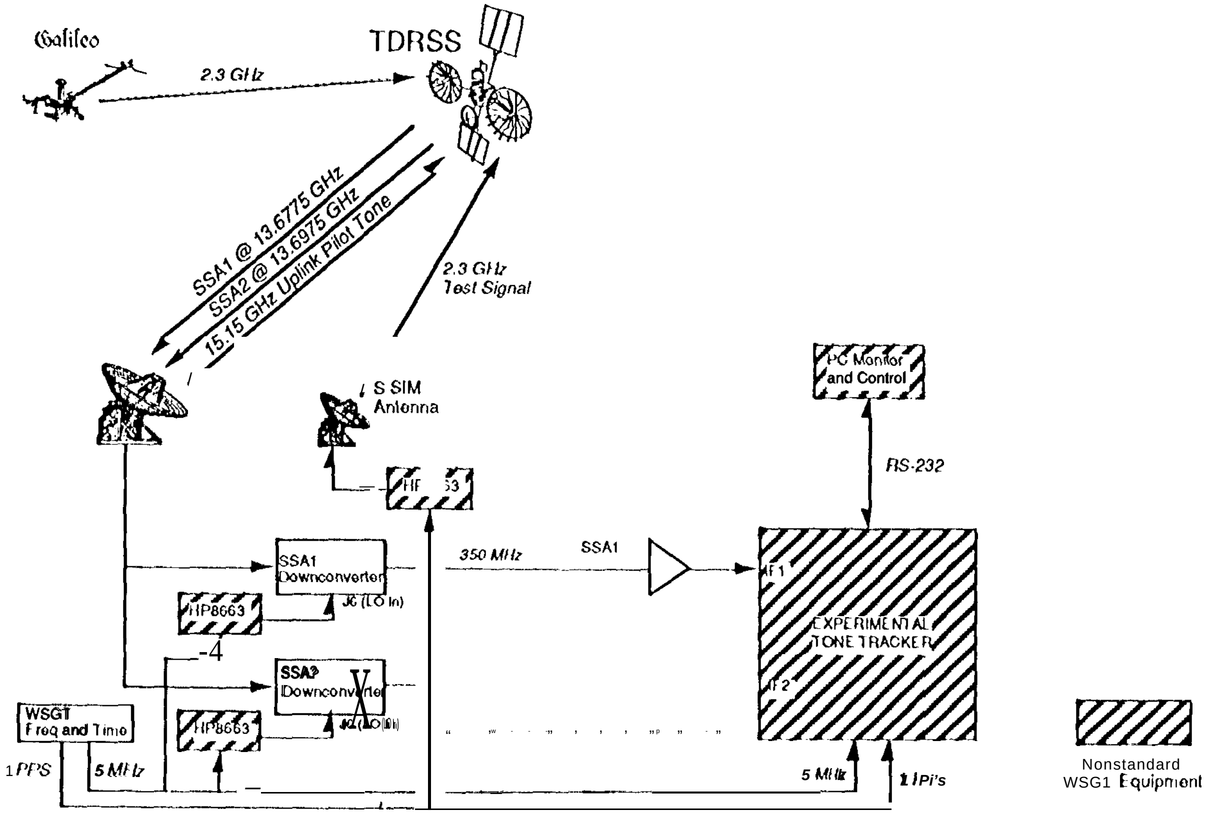
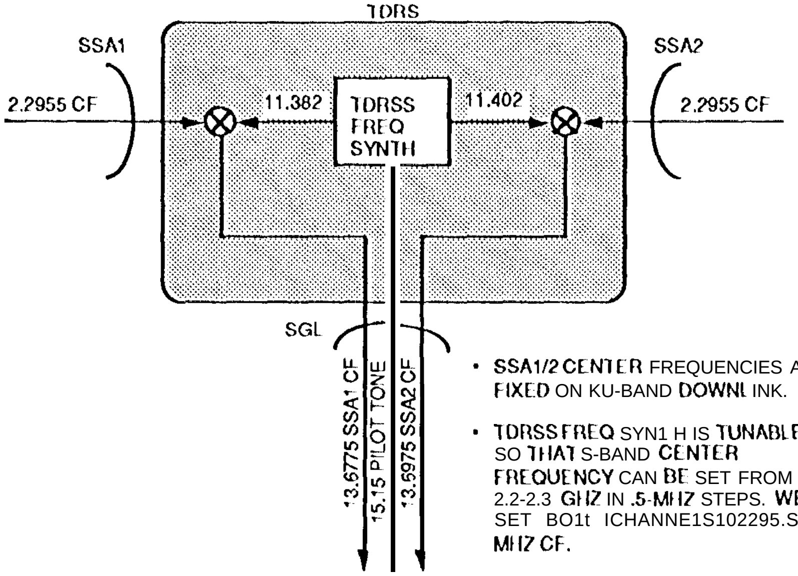


Figure 3: Experiment configuration for tracking Galileo using the TDRS-62W satellite.



- SSA1/2 CENTER FREQUENCIES ARE FIXED ON KU-BAND DOWNLINK.
- TDRSS FREQ SYNTH IS TUNABLE SO THAT S-BAND CENTER FREQUENCY CAN BE SET FROM 2.2-2.3 GHZ IN .5-MHZ STEPS. WE SET BOTH CHANNELS TO 2295.5 MHZ CF.

Figure 4: Frequency scheme on board TDRS. A 15.15-GHz uplink pilot tone is used to coherently translate the 2.3-GHz S-band signal received at each SA antenna to 13.7 GHz for relay to WSGT.

Simultaneous to the Galileo tracking, an S-band coherent test signal was transmitted at WSGT and received in the other SA antenna of TDRS-62W, where it was also frequency translated and re-transmitted back to WSGT. This signal was downconverted in a similar way and tracked in the other IF channel of the ETT. There were two motivations for including this calibration test signal. First, it provided a valuable real-time check of the end-to-end performance of the TDRSS system, including the modifications to the downconverters and the ETT processor, Secondly, the measured phase of the test signal provided an accurate calibration of any delay changes in the link between TDRS-62W and WSGT. Since the TDRS space-to-ground link is at 13.7 GHz, any delay changes along the TDRS-WSGT link induce phase changes with an effective frequency of twice this, or nearly 30 GHz. Thus tropospheric fluctuations and/or unmodeled spacecraft motion along the TDRS-WSGT line-of-sight can lead to significant corruption of the relayed Galileo Doppler signal. (Unmodeled TDRS motion along the Galileo-TDRS line-of-sight, on the other hand, enters only at the much lower frequency of 2.3 GHz.) The observation scheme used for this Galileo tracking experiment is very similar to the configuration used to support a demonstration of Orbiting Very Long Baseline Interferometry (OVLBI) using the TDRSS in 1986 [4], except that for the present experiment the SA antenna points at the Galileo spacecraft rather than at an extragalactic radio source. in fact, it was based on the successful OVLBI experience that the Galileo tracking experiment was proposed,

Roughly the first two hours of TDRSS tracking overlapped with the two-way Doppler arc at Canberra. During this period, the Galileo carrier was phase-locked to an uplink signal received from the Canberra DSN site, Galileo entered the field-of-view of the TDRS-62W antenna at 11:47 GMT, and at 12:00 GMT the S-band carrier, relayed by the TDRS, was acquired at WSGT. The Galileo signal was tracked continuously in three-way mode until 13:45 GMT when, just prior to setting below the Canberra horizon, Galileo switched to a one,-way non-coherent downlink signal, phase-locked to the on-board ultra-stable oscillator. At 13:46 GMT we acquired this one-way signal and successfully tracked it through perigee and out to the TDRS-62W FOV limit, which was reached at 15:34 GMT. Figure 5 shows the actual received power and frequency of the Galileo signal during the one-way portion of the TDRSS tracking. (Note than one can actually see the first sidelobe

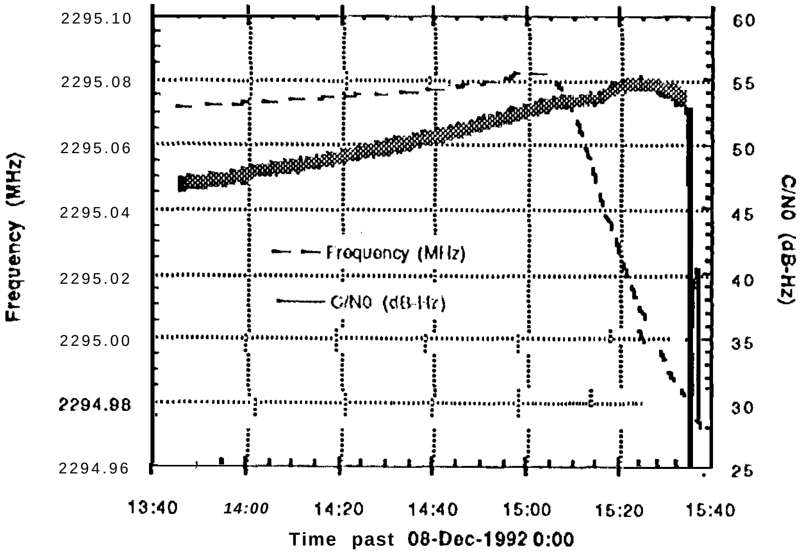


Figure 5: Received frequency and carrier power-to-noise spectral density ratio for the one-way portion of the Galileo Earth-2 TDRSS coverage.

of the TDRSS antenna in the plot of C/N_0 *vs.* time at the end of the pass, after the TDRS FOV limit is reached,)

During the actual tracking pass, we utilized the multi-channel capability of the ETT baseband receiver by tracking the Galileo Doppler signal with two separate phase-locked tracking loops. The two 3rd-order loops ran at different loop bandwidths to provide additional robustness throughout the tracking arc, particularly during the high phase

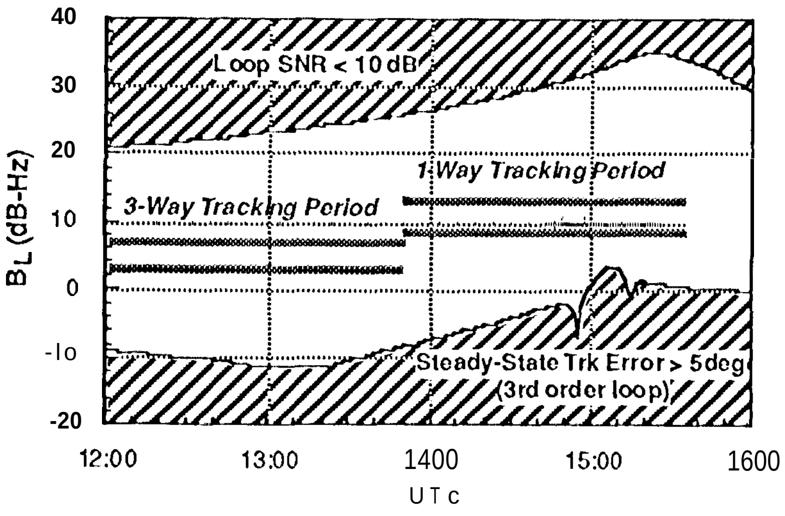


Figure 6: Tracking loop bandwidths employed during the three-way and one-way tracking periods, relative to the constraints imposed by loop SNR and steady-state tracking error considerations.

dynamics experienced near perigee. During the three-way tracking period (12:00 - 13:45), loop bandwidths of 2 Hz and 5 Hz were used, while during the one-way tracking period (13:46 - 15:34) the loop bandwidths were increased to 7 Hz and 20 Hz. These bandwidths were chosen with the goal of simultaneously maintaining at least 10 dB of loop SNR while also keeping the static phase error, due to higher-order phase derivatives, below 5 deg. The tracking passes were fully simulated prior to the experiment, based on the predicted Galileo - TDRS-62W link and ***a priori*** Galileo trajectory, to verify that the chosen loop bandwidths would satisfy these tracking criteria. Both the narrow- and wide-bandwidth tracking loops maintained lock throughout the three-way and one-way portions of the perigee tracking.

DATA PROCESSING

Doppler observables were generated from the carrier phase measurements made by the ETT at the White Sands ground station. The phase measurements are affected by the relative motions of the Galileo spacecraft, the TDRS relay satellite, and the ground station. To be compatible with modeling used to analyze radio metric data by the Galileo Navigation Team [5], the Doppler data were reformulated so as to appear to have been received at a fictitious earth-fixed site located at the nominal TDRS position. The details of the signal processing are given in this section.

Consider the case of one-way data, where the Galileo spacecraft transmits an S-band carrier signal derived from its onboard oscillator, the signal is transponder by TDRS, and then the transponded signal is received at White Sands. At TDRS, the spacecraft signal is upconverted to Ku-band by mixing with a local oscillator derived from a pilot tone Ku-band uplink from White Sands to TDRS. The signal received at White Sands is downconverted to baseband and input to the ETT, where the Galileo carrier phase is extracted by a phase-locked loop. As described earlier, an S-band test tone is also uplinked from White Sands to TDRS, upconverted to Ku-band, transponded to White Sands, and downconverted and input to the ETT. This test tone signal is combined with the Galileo signal to eliminate instability in the Ku-band uplink from White Sands to TDRS and to eliminate instability in the frequency upconversion at TDRS.

Some notation must be introduced to define the observable. Let $\rho_{\alpha\beta}$ be the one-way range from point α to point β, defined as the proper time of signal reception at point β minus the proper time of signal emission from point α. Range computations are needed for four points: the Galileo spacecraft "G", the TDRS relay satellite **"T"**, the White Sands ground station **"W"**, and the fictitious earth-fixed TDRS site "T_n". Denote the frequencies of the Galileo onboard oscillator, the White Sands pilot tone uplink, and the White Sands test (one uplink by fuse, f_{pilot}, and f_{test}, respectively. The Galileo spacecraft signal and the White Sands test tone signal are upconverted at TDRS by $k_1 f_{pilot}$ and $k_2 f_{pilot}$, respectively, where k_1 and k_2 are multiplicative factors relating the coherently generated upconversion 1.0 signals with the uplink pilot frequency. Let ϕ_a and ϕ_b denote the RF received phase, at White Sands, of the Galileo carrier signal and of the test tone signal, respectively. Finally, denote the received RF phase, linearly combined to eliminate the effects of the pilot tone uplink and the frequency conversion at TDRS, by ϕ_{RF}. Nominal values for all model terms are given in Table 1. The received phase is related to the transmitter frequencies and the one-way ranges by

$$\phi_{RF}(t_4) = \phi_a(t_4) - \frac{k_1}{k_2}\phi_b(t_4) = f_{USO}[t_4 - \rho_{TW}(t_4) - \rho_{GT}(t_3) - t_0] - \frac{k_1}{k_2} f_{test}[t_4 - \rho_{TW}(t_4) - \rho_{WT}(t_3) - t_0''] \qquad (1)$$

where t_4 is the proper time of signal reception at White Sands and t_3 is the proper time of signal transpond at TDRS. The constants to and t_0'' are unknown epochs related to the integer ambiguity in the carrier cycle. Eq. (1) may be rewritten as

$$\phi_{RF}(t_4) - f_{USO}[\rho_{GTn}(t_4) - \rho_{TW}(t_4) - \rho_{GT}(t_3)] - \frac{k_1}{k_2} f_{test}[t_4 - \rho_{TW}(t_4) - \rho_{WT}(t_3) - t_0''] = f_{USO}[t_4 - \rho_{GTn}(t_4) - t_0]. \qquad (2)$$

The left hand side of Eq. (2) is the observed phase adjusted by modeled values of certain ranges, while the right hand side of Eq. (2) is a representation of one-way phase received at the fictitious earth-fixed TDRS site that is compatible with the data analysis models used for navigation of Galileo. This reformulation is useful only to the extent that the errors in the model terms added to the left hand side do not hide the effects of interest in the data. The reformulated one-way Doppler observable is

$$F1_{observed} = f_{USO} - (\phi_c - \phi_s)/T_c$$

where

the time-tag is the center of the count interval,

T_c is the count interval (see),

ϕ_s is the reformulated observed phase given by the left hand side of Eq. (2) at the start of the count interval (cycles),

ϕ_c is the reformulated observed phase given by the left hand side of Eq. (2) at the end of the count interval (cycles).

Doppler observables for the case of three-way data, where a signal is uplinked from a DSN ground station, transponded by the Galileo spacecraft, transponded again by the TDRS relay satellite, and then received at the White Sands ground station, are generated in an analogous fashion. Using the same notation as in Eq. (1), the received three-way phase is given by

$$\phi_{RF}(t_4) = \phi_a(t_4) - \frac{k_1}{k_2}\phi_b(t_4) = \frac{240}{221} 96\, f_q [t_4 - \rho_{TW}(t_4) - \rho_{GT}(t_3) - \rho_{DG}(t_2) - t_0'] - \frac{k_1}{k_2} f_{test}[t_4 - \rho_{TW}(t_4) - \rho_{WT}(t_3) - t_0''] \qquad (3)$$

where f_q is the exciter frequency at the DSN uplink station DSS-42 in Canberra, the uplink site is denoted “D” in the one-way ranges, t_2 is the proper time of signal transpond at Galileo, and t_0' is an unknown epoch related to the integer ambiguity in the carrier cycle. As for one-way data, Eq. (3) is reformulated as

$$\phi_{RF}(t_4) - \frac{240}{221}\, 96\, f_q \left[\rho_{GTn}(t_4) - \rho_{TW}(t_4) - \rho_{GT}(t_3) - \rho_{DG}(t_2) + \rho_{DG}(\hat{t}_2)\right]$$

$$+ \frac{k_1}{k_2} f_{rost} \left[t_4 - \rho_{TW}(t_4) - \rho_{WT}(t_3) - t_0''\right] =$$

$$\frac{240}{221}\, 96\, f_q \left[t_4 - \rho_{GTn}(t_4) - \rho_{DG}(\hat{t}_2) - t_0'\right] \qquad (4)$$

where $\hat{t}_2$ is the proper time of signal transpond at Galileo for a signal received at the fictitious earth-fixed TDRS site at time t_4. The reformulated three-way Doppler observable is

$$F3_{observed} = \frac{240}{221}\, 96\, f_q - (\phi_e - \phi_s)/T_c.$$

Table 1

NOMINAL VALUES OF PARAMETERS USED IN THE OBSERVABLE MODEL

Symbol		Nominal Value
G	Galileo spacecraft	
f_{USO}	onboard oscillator frequency	2294997678.17 Hz
T	TDRS relay satellite	
k_1	Galileo channel multiplication factor	11402/15150
k_2	test tone channel multiplication factor	11382/15150
T_n	Fictitious earth-fixed TDRS site	
	spin radius	42149.527 km
	east longitude	298.0609 deg
	height above equator	-12.451 km
W	White Sands ground station	
f_{pilot}	pilot tone uplink frequency	15.15×10^9 Hz
f_{test}	test tone uplink frequency	2295.5×10^6 Hz
	spin radius	5385.663 km
	east longitude	253.391455 deg
	height above equator	3408.188 km
	zenith troposphere - dry	2.055 m
	zenith troposphere - wet	0.043 m
D	DSS-42 ground station	
f_q	uplink exciter frequency	22027270.117,
	spin radius	5205.352492 km
	east longitude	148.98126256 deg
	height above equator	-3674.582214 km
	mount type	equatorial
	axis offset	6.706 m
	zenith troposphere - dry	2.152 m
	zenith troposphere - wet	0.136 m

The best available trajectories for Galileo and the TDRS relay satellite were used in the reformulation, The Doppler error introduced by the reformulation is estimated to be less than $2\text{x}10^{-11}$ s/s, corresponding to a velocity error of 6 mm/s, The limiting error source is a 20-m uncertainty in the position of the TDRS relay satellite; the signature introduced in the data by this error has the form of a slow drift over the interval of perigee passage.

RESULTS

The altitude of the flyby at perigee was 303 km; hence, both Earth's gravity field and atmospheric drag were important to the orbit determination, The gravity field, modeled by spherical harmonics to degree and order 40, was obtained by truncating the Goddard JGM-2 70x 70 field. Outside of some experiments to include GM and J2 in the fits, we made no adjustments to the 40 x 40 field. We accounted for atmospheric drag by two methods, In the first we solved for an impulsive three-dimensional velocity correction at perigee, and in the second we solved for the drag coefficient CD included in JPL's exponential drag model.

The two methods yielded similar fits to the data, Within an uncertainty of eight percent, both methods yielded a decrease in velocity along track of -5.9±0.2 mm/s. *A* ***priori*** predictions for the drag-induced velocity change, based on the Jacchia-Roberts model, were -6.2±4.0 mm/s [5], clearly consistent with the observed velocity change. By contrast, DSN data from the December 1990 Earth flyby, at altitude 956 km, indicated an unexplained increase in along-track velocity of 4 mm/s, after accounting for the much smaller drag effects. Given the uncertainty in drag models, we cannot conclusively rule out the possibility that a similar increase occurred at Earth 2. For example, an unmodeled increase of 4 mm/s and a drag decrease of -10 mm/S would be compatible with our results and our ***a priori*** atmospheric model. Significantly larger anomalous velocity increases, however, would appear inconsistent with the drag model,

Starting with the Galileo Navigation Team's post-flyby reconstruction of the trajectory, we made several least-squares fits to the reduced TDRSS one-way data, These data were referenced to the spacecraft's ultra-stable crystal oscillator (USO). The fits differed from one another in the specific parameters estimated and in the specific DSN Doppler and ranging data included in the fit, Representative plots of one-way TDRSS residuals (observed minus computed values) near perigee for two different cases are displayed in Figure 7. The Doppler residuals in units of Hz have been converted to velocity units by using the S-band transmitted frequency of 2.29 GHz.

in these fits, all of the DSN Doppler and range data from 00:00-22:00 GMT on 8-Dec-1992 were included along with the TDRSS one-way and three-way data. For the upper plot, the estimated parameters included the Galileo state vector, a drag coefficient, an adjustment to the TDRS-62W position, and a frequency bias for the Galileo oscillator; no other parameters were estimated, An obvious signal is apparent shortly before perigee. The additive noise reflects the short-term instabilities of the USO. This feature remains even when fitting only the TDRSS one-way data, as well as for other combinations of TDRSS and DSN data,

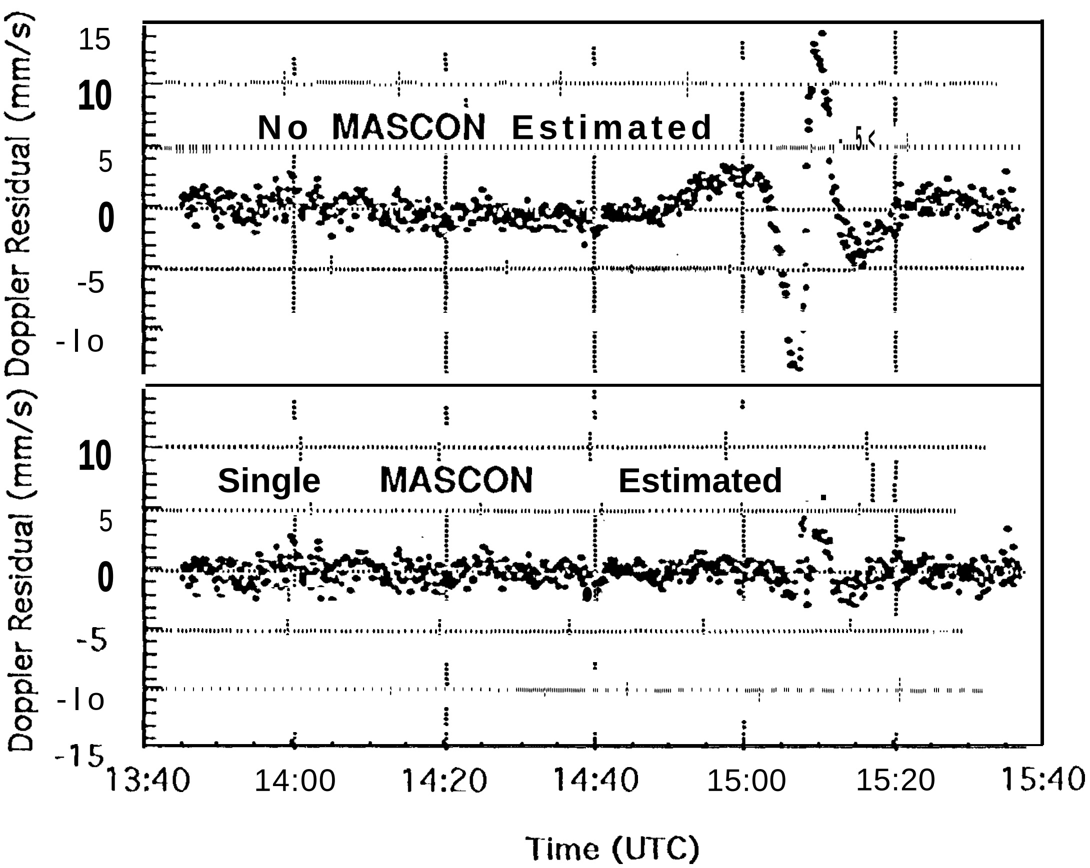


Figure 7: Doppler residuals for the one-way **Galileo-TDRS** perigee period,

The lower plot in Figure 7 shows the residuals when a single point mass MASCON is added to the list of estimated parameters. The single point mass is able to significantly reduce the Doppler signature near perigee. However, preliminary analysis suggests that the required mass is unrealistically large, compared to current uncertainties in the Earth gravity model. We are also investigating whether any effects on the TDRS, such as the rapid antenna slewing near perigee, could induce the observed signature. More work is needed before we can claim to understand the real cause of these TDRSS residuals.

SUMMARY

The TDRSS was successfully used to provide continuous tracking of the 2.3-GHz (S-band) carrier signal from Galileo during the Earth gravity-assist flyby on December 8, 1992. The TDRSS was configured to receive the Galileo carrier in one SA antenna and an S-band test signal from WSGT in the other SA antenna. Both signals were relayed to WSGT, where a digital tracking receiver was installed to provide carrier phase tracking. Doppler observables were formulated to allow processing using the standard Galileo navigation software. Analysis of the DSN and TDRSS data provides no indication of a repeat of the 4 mm/s velocity anomaly observed during the first Galileo Earth flyby in 1990, but atmospheric drag uncertainty for the second flyby, due to the lower perigee altitude, complicates the interpretation of the data, The one-way Galileo-TDRS Doppler data exhibit a feature prior to perigee which can largely be removed by adjusting the Earth gravity model with the addition of a single point mass; this feature is still being investigated.

ACKNOWLEDGMENTS

The research described in this paper was carried out by the Jet Propulsion laboratory, California Institute of ‘J’ethnology, under a contract with the National Aeronautics and Space Administration. Many people and organizations helped in enabling these results. We thank the management and staff of the White Sands Ground Terminal for facilitating these observations; special thanks go to James Gavura and Robert Gonzalez. Also, Frank Vaughn, Emery Kopf, James Jackson, and Mike Maher from Goddard Space Flight Center provided invaluable assistance, Finally, Garth Franklin and Mark Smith of JPI. supplied critical logistical support.

REFERENCES

[1] Kallemeyn, P., “Observations from Galileo Earth-1 ftyby reconstruction efforts,” GLL-NAV-91-62, Jet Propulsion laboratory, (Internal Document), April 3, 1991.

[2] Beyer, P. E. and M. M. Andrews, “Galileo Post-Gaspra Cruise and Earth-2 Encounter," The Telecommunications and Data Acquisition Progress Report 42-113, Jet Propulsion Laboratory, vol. January-March 1993, Jet Propulsion 1.aboratory, pp. 106-117, May 15, 1993.

[3] Thomas, J. B., “Functional Description of Signal Processing in the Rogue GPS Receiver," JPL Publication 88-15, Jet Propulsion Laboratory, 1988.

[4] Levy, G. S., *et al.*, "Very Long Baseline Interferometric Observations Made with an Orbiting Radio Telescope," Science, **234**, 187-189, 1986.

[5] Moyer, T. D., "Mathematical Formulation of the l>ouble-Precision Orbit Determination Program (DPODP)," J])], Technical Report 32-1527, Jet Propulsion laboratory, May 15, 1971.

[6] Garner, Gregory J., "Results of Earth 2 Drag Analysis,” GLL-NAV-93-44, Jet Propulsion laboratory, (Internal Document), March 30, 1993.