RUBIDIUM ULTRA-STABLE OSCILLATORS AT TITAN: THE HUYGENS DOPPLER WIND EXPERIMENT

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Abstract. The Doppler Wind Experiment (DWE) is one of six investigations to be performed during the Titan atmospheric descent of the ESA Huygens Probe. The primary scientific objective is to measure the direction and strength of Titan’s zonal winds with an accuracy better than $1\ m\ s^{-1}$. The Probe’s wind-induced horizontal motion will be derived from the residual Doppler shift of its S-band radio link to the Cassini Orbiter, corrected for all known orbit and propagation effects, from the beginning of the mission (altitude: ~160 km) down to impact on the surface. The DWE Instrumentation consists of Rb-based Ultra-Stable Oscillators used to (a) generate the transmitted signal from the Probe and (b) extract the frequency of the received signal on the Orbiter. The capabilities of these USOS under the rugged experimental conditions on Titan and some results from the DWE pre-launch test program are described.

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1 Introduction

The Doppler Wind Experiment (DWE) of the Huygens Mission is a radio tracking investigation designed to measure wind velocities in the atmosphere of Saturn’s moon Titan (Atkinson et *al.*, 1992; Bird et *al.*, 1997). A similar experiment under considerably more severe environmental conditions was performed with the Galileo Probe at Jupiter (Pollack et al., 1992; Atkinson et al., 1996). The primary scientific objective of DWE is a height profile of the zonal (east-west) wind speeds as deduced from the Doppler shift of the Probe’s radio signal to the Cassini Orbiter. As with the Galileo Probe descent at Jupiter (Folkner *et* al., 1996), prospects are good that additional measurements to obtain an additional wind component can be recorded at a large ground-based radio telescope. Upon applying corrections for the motion of the Orbiter and the Probe descent velocity, it is estimated that the horizontal drift due to winds can be measured to a precision better than 1 m/s. Radio propagation effects on the received frequency can be shown to be negligible for the Huygens DWE geometry (Bird, 1997). Measurements commence upon establishment of the link shortly after parachute deployment at a nominal altitude ~160 km and continue for at least 135± 15 minutes until touchdown on Titan. Although post-impact survival of the Probe is not guaranteed, the special Huygens receivers on the Orbiter will continue to monitor a possible Probe broadcast from Titan's surface for a minimum of 30 minutes.

Specific secondary science objectives of DWE include measurements of: (a) Doppler fluctuations to determine the turbulence spectrum and possible wave activity in the Titan atmosphere; (b) Doppler and signal level modulation to monitor Probe descent dynamics (e.g., spinrate/spinphase, parachute swing); (c) Probe coordinates and orientation during descent and after impact on Titan. DWE will complement remote-sensing observations of temperatures and winds from the Cassini Orbiter, providing "ground truth" for the zonal wind retrievals from the Composite Infrared Spectrometer (CIRS) experiment.

A potentially severe constraint on the accuracy of the DWE wind measurement is the stability of the oscillators used to generate the radio signal on the Probe and receive it on the Orbiter. The required long-term frequency drift stability ($\delta f/f \lesssim 2 \cdot 10^{-10} \Rightarrow \delta f \lesssim 0.4$ Hz at S-band) is expected to be met by using rubidium-based ultra-stable oscillators in both the transmitter (TUSO) and receiver (RUSO).

The present paper summarizes the science objectives and the planning/execution of the DWE investigation. This is followed by a short description of the DWE-instumentation and its development within the context of the Huygens pre-launch test program. More information about DWE may be found in Bird *et al.* (1997), together with descriptions of the other investigations and the Huygens mission in general (Lebreton, 1997).

2 Titan winds: A brief overview

Our only previous close look at Titan's atmosphere was during the Voyager 1 flyby on November 12, 1980. Doppler tracking data collected during Earth occultation were used to derive Titan's vertical temperature-pressure curve (Lindal et al., 1983) that indicated a surface temperature of 97±7K. The temperature was seen to decrease with altitude to a minimum of ~70 K at the tropopause near 40 km (weak greenhouse effect).

The featureless orange-brown haze of the upper atmosphere prevented observation of the surface at optical wavelengths. Motions of purported methane clouds in the lower atmosphere were thus not available for inferring atmospheric circulation. Indirect evidence for strong zonal winds, however, was the temperature difference from pole to equator derived from infrared observations (Flasar *et al.* 1981). Requiring conservation of angular momentum, it is necessary that a gradient, in latitudinal temperature be accompanied by bulk motion in the zonal direction. Flasar et *al.* (1981) suggested that the zonal wind would increase monotonically with height, approaching values ~100 m/s in the upper stratosphere at mid-latitudes near 200 km. Ironically, the simple theory can be satisfied by winds blowing either west-to-east (prograde: in the direction of Titan's rotation) or east-to-west (retrograde). Even stronger winds would be attained at lower latitudes. A recent review of evidence supporting the existence of Titan's zonal winds bass been published by Flasar et *al.* (1997).

The hypothesized zonal flow on Titan, however, is still a fundamental enigma in the theory of atmospheric dynamics. Even the meridional and vertical winds, although thought to be much smaller, are largely unknown. Only recently have general circulation models (GCMs) been adapted to the study of atmospheric superrotation on Titan (Del Genio et *al.*, 1993; Hourdin *et al.*, 1992). ‘The picture becomes even less clear at altitudes within the planetary boundary layer (~5 km), where surface effects can rotate and shear the mean flow.

Some independent evidence for winds on Titan has emerged from recent Earth-based observations. Hubbard et *al.* (1993) reported photometric measurements of optical limb extinction during Titan's occultation by a relatively bright star. The observations could be explained in terms of a nonspherical atmosphere, implying zonal winds ranging from 80 m/s to 170 m/s at an altitude near 250 km. Infrared heterodyne observations of Titan's 12 μm ethane emission, originating from heights near 200 km, indicate that the winds are *prograde* and have speeds of the order of 80 m/s (Kostiuk 1993, private communication). Finally, near-infrared images of Titan obtained with the refurbished planetary camera (WF/PC2) of the Hubble Space Telescope (Lorenz et *al.*, 1995; Smith et aJ., 1996) have been closely examined for cloud motions. Unfortunately, the quest has been thus far unsuccessful.

3 DWE Planning and Execution

Geometry was an essential element in designing the DWE. The Huygens descent mission on Titan is presently scheduled to occur on 27 November 2004, about five months after Cassini arrives at Saturn and seven years after launch. Approximately 22 days prior to its mission, the Probe is separated from the Orbiter and targeted for entry into Titan's atmosphere. The Orbiter then performs a deflection manuever into a trajectory that delays its arrival by about four hours and misses the Titan surface by 1500 km.

The Probe is decelerated at atmospheric entry up to a maximum of 16.1 g at an altitude near 250 km. Parachute deployment at a speed near Mach 1.5 marks the start of the descent phase (time = to). A smaller drogue parachute is deployed at t_0 + 15 minutes in order to decrease the descent time. The radio link to the Orbiter is established by t_0 + 150 s.

It was originally planned to target the Probe to a location near Titan's central meridian as viewed from the approaching (1-biter. This resulted in an unfavorable DWE geometry because of the extremely small east/west projection on the line-of-sight to the Orbiter. The effective Doppler shift from the zonal drift would thus be too small to be measured. After considerable negotiation, it was decided to move the target about 700 km to the east while retaining the same atmospheric entry angle. The present nominal target position is latitude 18°N, longitude 152°W, for which the mean angle between the line-of-sight and the zonal direction during the Huygens mission will be 64°. The targeting errors about this nominal position are ±452 km in longitude and ±59 km in latitude. The new entry site also improves the experimental geometry for coordinated Doppler measurements along the two lines-of-sight from Probe-to-Orbiter and Probe-to-Earth, respectively. The horizontal wind projections for these two viewing directions are now separated by ~20°. A prograde zonal wind would shift the Probe's final touchdown site to the east of its atmospheric injection point, thereby improving the Doppler projection.

4 DWE Instrumentation

4.1 End-to-end design

Of the six Huygens investigations, DWE is the only one with instrumentation on both the Probe and Orbiter (in the Probe Support Equipment–PSE). The DWE experimental configuration is shown in Fig 1.

The DWE-TUSO is used to generate the radio signal of chain A (Tx A). An internal TCXO oscillator serves as back-up in the event of a TUSO failure. The eventual decision to use the TUSO or its backup will be taken a few days prior to Probe-Orbiter separation. The TUSO output frequency at 10 MHz is multiplied by 204 to S-band and transmitted to the dedicated Probe receiver (Rx A) in the PSE on the Orbiter. The semiannual cruise checkouts can be conducted with the radio frequency built-in-test equipment (RF-BITE) across the Umbilical Separation Mechanism (US M). At Titan the signal is amplified for free-space transmission via the Probe Antenna (PTA) to the Orbiter's HGA.

Timing and signal generation for Rx A are controlled by the DWE-RUSO. In order to maintain interchangeability, the RUSO was fabricated as an exact clone of the TUSO. Consistent with the Probe strategy, an integrated TCXO can be substituted for the RUSO if needed. The phase-locked loop control in Rx A is monitored by a numerically controlled oscillator (NCO), the output of which is recorded to provide the DWE frequency measurement at a sample rate of 8 Hz. The signal level (AGC) is monitored in parallel at the same sample rate. In addition to these DWE "science data", temperatures and internal lock status of TUSO and RUSO are recorded as housekeeping data.

The TUSO will be powered well in advance of the start of transmission from the Probe ($\sim$30 minute head start), in order to warm up and achieve the required frequency stability. The RUSO will be switched on even earlier, together with the rest of the PSE on the Orbiter.

4.2 Transmitter and Receiver USO programs

The DWE ultrastable oscillators, the first rubidium oscillators used in a deep space mission, were developed and constructed by Daimler-Benz Aerospace (DASA), Satellite Systems Division, Ottobrunn, Germany. The key ingredient of the DASA design concept is the Rb-resonator in a "physics package" supplied by Efratorn Elektronik GmbH. The final flight model units, a TUSO, a RUSO and a spare, were delivered to the Probe System FM Test Program in early 1996.

The DWE USOS must survive the Cassini/Huygens launch, cruise phase, and atmospheric entry/descent on Titan. In addition to the required fast warm-up time, another major driver in the selection of a rubidium ultrastable oscillator, was the high level of mechanical loads during the Huygens entry phase. The frequency stability required in the DWE instrument specification ($\delta f_0/f_0$ < 2.10-10, f_0 = nominal output frequency) could not be guaranteed with a state-of-the-art quartz oscillator. It was feared that the continuously changing mechanical stresses at entry and the following variation in pressure from one millibar to the surface presure of 1.5 bar could cause deformation of the internal quartz fastening system and produce nonreproducible frequency offsets and relaxation curves. A rubidium oscillator is much less susceptible to these effects because the nominal output frequency is locked to the very stable frequency of the rubidium ground-state hyperfine transition.

A block diagram of the USO unit is shown in Fig. 2. The USO consists of the Physics Package (rubidium resonance cell and lamp) and printed circuit boards integrated into an aluminium box (Faraday cage). Starting at upper left and moving clockwise in Fig. 2, the separate elements are: (*i*) Lamp Board: controls power and heating for the Rb lamp. (ii) Physics Package: consists of the Rb lamp, Rb resonance cell and se-cut quartz crystal, the temperatures of which are monitored by three analogue sensors. (iii) Oscillator Board: provides the 10 MHz output via VCXO quartz through a buffer amplifier. (iv) Servo Board: generates the error signal for the VCXO from the photocurrent of the Physics Package and provides a telemetry lock indicator when the output is phase-locked to the Rb resonance frequency. (v) Synthesizer Board: upconverts the output signal from the VCXO to the Rb resonance frequency. (vi) DC/DC converter: converts external supply voltages of 28/30 V (TUSO/RUSO) to 5 V and 17 V.

The actual physical and electrical characteristics of the DWE-USO, as determined during the extensive qualification test program at unit level, are presented in Table 1. The expected decreases in USO steady-state power consumption and warm-up time (until Rb-lock) with increasing ambient temperature are illustrated in Fig. 3.

Table 1: DWE-USO physical and electrical characteristics

Physical parameters		
Mass [g]	1898±2	radiation shielding: 150
Dimensions [mm]	170x117x119	(Lx W×H)
Frequency parameters		
Output Frequency [MHz]	10	±0.1 Hz
Frequency long-term drift	1.4.10-9	$\delta f_0/f_0$ over 3 hours
Allan variation	$3\cdot10^{-11}$	$\tau = 1$ s
	$6\cdot10^{-12}$	$\tau = 10$ s
Phase Noise [dBc/Hz]	< ..75	*df* = 1 Hz
	<-110	*df* = 10 Hz
	<-130	*df* = 100 Hz
	<-130	*df* = 1000 Hz
Signal level/Waveform		
Output Signal Level [dBm]	0±2	into 50 Ω impedance
harmonics [dBc]	<--45,--36	2^{nd}, 3rd, respectively
Spurious signals [dBc]	< –60	up to 50 MHz
Return loss [dB]	<--30	50 Ω impedance
DC Power		
Supply Voltage [V]	$28^{+0.35}_{-0.633}/30^{+1.5}_{-3.38}$	TUSO / RUSO
Warm-up Power [W]	< 18.4	<40 min (Fig. 3)
DC current [mA]	< 675	System limit: 0.7 A
Energy [Wh]	< 32.5	worst case (rein temp)

The USO long-term frequency drift stability requirement of $\delta f_0/f_0 \leq$ 1.4.10-9 (i.e., the allowed output frequency deviations during the maximum possible mission time of 3 hours) is critical for a successful Doppler Wind Experiment. 'This figure of stability was determined during the qualification test program over an expanded range of temperatures (–300 < T <

60°) in vacuum (0.1 mbar) and ambient pressure. The original USO specification of $\delta f_0/f_0 \leq 2.\,10^{-10}$ could be met only after a warm-up time of greater than 45 minutes over a more restricted range of temperature (–20° < T < 40°). Even for the somewhat degraded USO performance, however, the maximum measurement error of the line-of-sight velocity due to intrinsic USO stability will still be only about ±40 cm/s over the entire Huygens mission. This error is of the order of the errors expected from uncertainties in the reconstructed trajectories.

4.3 USO Performance during System Flight Model Tests

Short discussions of the unit level and engineering model (EM) test programs were given in Bird *et al.* (1997). An example from the Huygens Probe flight model test program is presented here.

The Huygens radio signal frequency recorded by the NCO in Rx A during the first FM Integrated System Test is shown as a function of time from start of test in the upper panel of Fig. 4. The first part of the test was performed using the internal TCXOs in the transmitter/receiver chain A. The TUSO/RUSO combination was switched from standby to operation at the time $t \simeq$ 104 min. The characteristics of the received frequency change at this point from a series of discontinuous jumps and unpredictable drifts to a stable value near the zero line (nominal for check-out mode with no Doppler shift). The lower panel of Fig. 4 shows a 30-minute interval of the upper trace on an expanded scale. The individual points are single measurements recorded at the sample rate of 8 Hz. The digitization of these measurements ($\Delta f \simeq$ 0.15 Hz, corresponding to $\sim$2 cm/s) is apparent in the discrete levels of this point cluster. The solid line is a running average over 80 continuous points (10 sec). The standard deviation of the two traces are 2.8 Hz and 0.29 Hz, respectively, consistent with the 80-fold increase in integration time.

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5 Conclusions

The main scientific goal of the Huygens Doppler Wind Experiment is to determine the velocity of Titan's horizontal winds at heights 0-160 km from frequency measurements of the Probe's radio signal recorded on the Orbiter. Similar Earth-based observations will be recorded in order to separate meridional from zonal drift motion. Adequate frequency stability is attained by using rubidium ultrastable oscillators to generate the transmitted signal and drive the electronics of the monitoring receiver. Final trajectory reconstruction and analysis of Probe dynamics using DWE data will provide valuable ancillary information that should enhance the overall scientific yield of the Huygens Mission.

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References

Atkinson, D. H., Pollack, J. B. and Seiff, A., Measurement of a zonal wind profile on Titan by Doppler tracking of the Cassini entry probe, Radio *Sci.* 25, 865-882, 1990.

Atkinson, D. H., Pollack, J. B. and Seiff, A., Galileo Doppler measurements of the deep zonal winds at Jupiter, Science 272, 842-843, 1996.

Bird, M. K., Atmospheric attenuation of the Huygens S-Band Radio Signal during the Titan Descent, in *Huygens:* Science Payload *and Mission,* ESA-SP 1177, in press, 1997.

Bird, M. K., Heyl, M., Allison, M., Asmar, S. W., Atkinson, D. H., Edenhofer, P., Plettemeier, D., Wohlmuth, R., Iess, L., and Tyler, G. L., The Huygens Doppler wind experiment, in *Huygens:* Science Payload and *Mission,* ESA-SP 1177, in press, 1997.

Del Genie, A. D., Zhou, W. and Eichler, T. P., Equatorial superrotation in a slowly rotating GCM: Implications for Titan and Venus, *Icarus* **101, 1-17, 1993.**

Flasar, F. M., Allison, M. and Lunine, J. I., Huygens Probe wind drift: science issues and recommendations, in *Huygens:* Science Payload and Mission, ESA-SP 1177, in press, 1997.

Flasar, F. M., Samuelson, R. E. and Conrath, B. J., Titan's atmosphere: temperature and dynamics, *Nature* 292, 693-698, 1981.

Folkner, W. M., Preston, R. A., Border, J. S., Navarro, J., Oestreich, M. and Wilson, W., Earth-based observation of Galileo Probe for Jupiter wind estimation, paper presented at the AGU Spring Meeting, Baltimore, 1996.

Hourdin, F., Talagrand, O., Sadourny, R., Courtin, R., Gautier, D. and McKay, C. P., Numerical simulation of the general circulation of the atmosphere of Titan, **Icarus, 117,** 358-374,1995.

Hubbard, W. B. et al., The occultation of 28 Sgr by Titan, Astron. *Astrophys.* 269, 541-563, 1993.

Lebreton, J.-P., Huygens science overview and mission description, in *Huygens: Science* Payload and Mission, ESA-SP 1177, in press, 1997.

Lindal, G. F., Wood, G. E., Holtz, H. B., Sweetnam, D. N., Eshleman, V. R. and Tyler, G. L., The atmosphere of Titan: An analysis of the Voyager 1 radio occultation measurements, *Icarus* 53, 348-363, 1983.

Lorenz, R. D., Smith, P. H. and Lemtnon, M. T., The search for clouds on Titan using HST imaging, BAAS 27, 1107, 1995.

Pollack, J. B., Atkinson, D. H., Seiff, A. and Anderson, J. D., Retrieval of a wind profile from the Galileo Probe telemetry signal, Space *Sci.* Rev. 60, 143-178, 1992,

Smith, P. H., Lemmon, M. T., Lorenz, R. D., Sromovsky, L. R., Caldwell, J. J. and Allison, M. D., Titan's surface, revealed by HST imaging, Icarus **119, 336-349,** 1996.

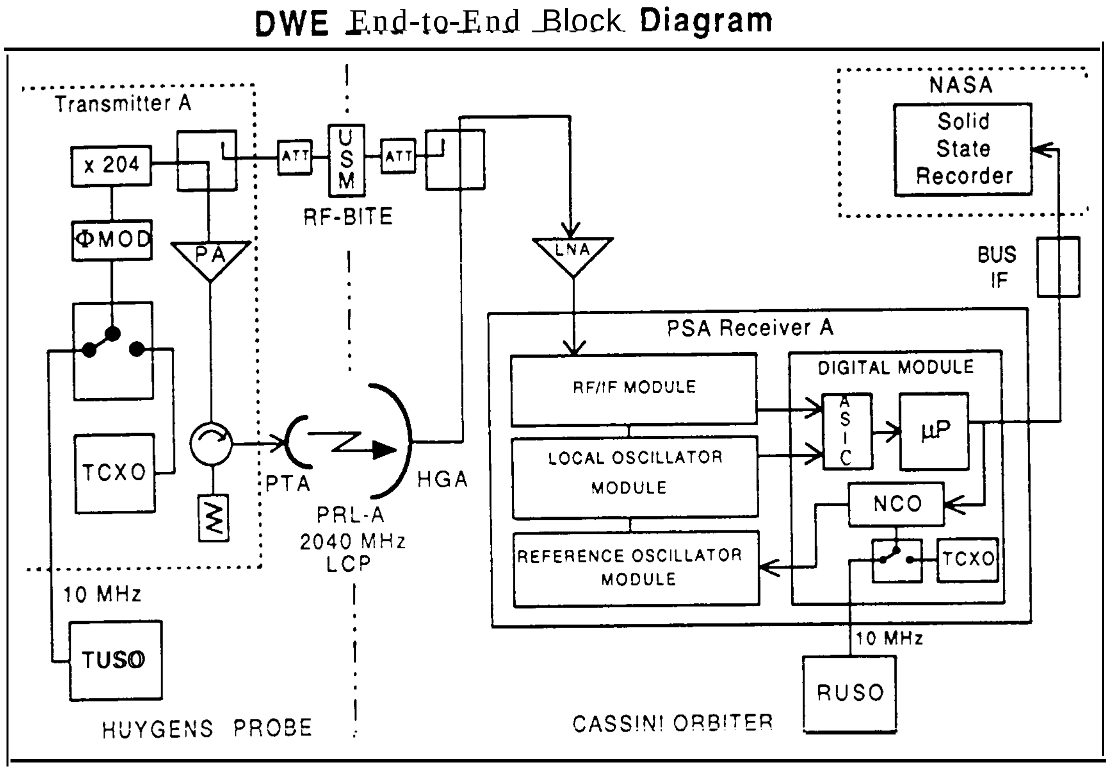

Fig. 1. DWE experiment configuration [reprinted from Bird *et* al., 1997].

DWE-USO Block Diagram

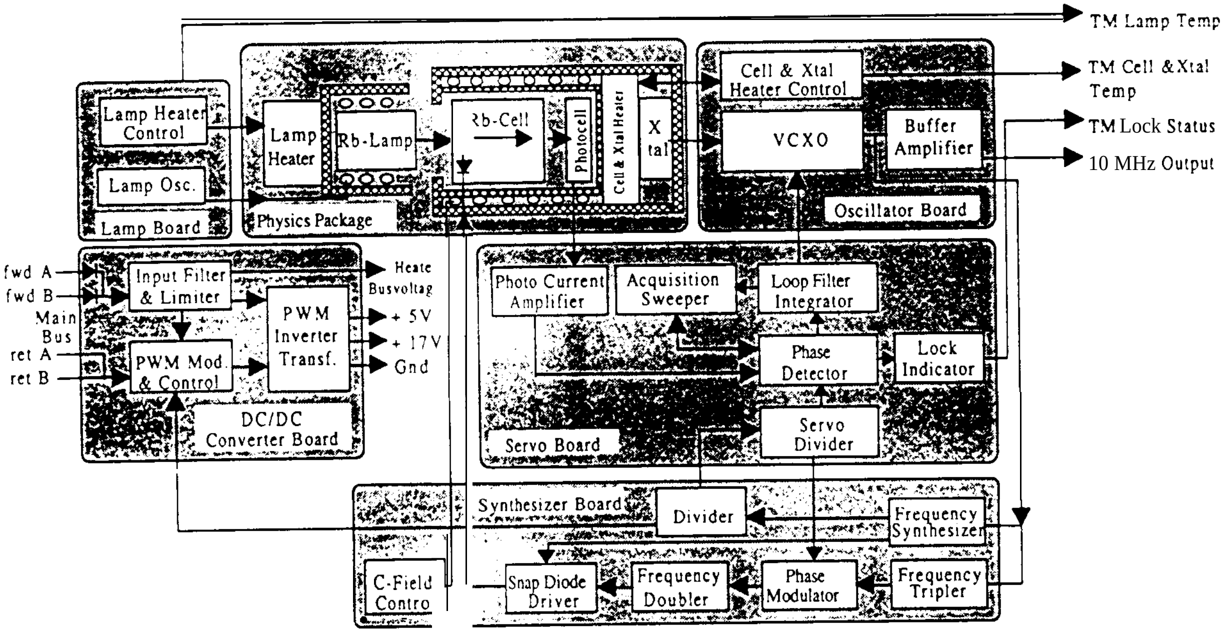

Fig. 2. DWE-USO block diagram [reprinted from Bird et *al.*, 1997].

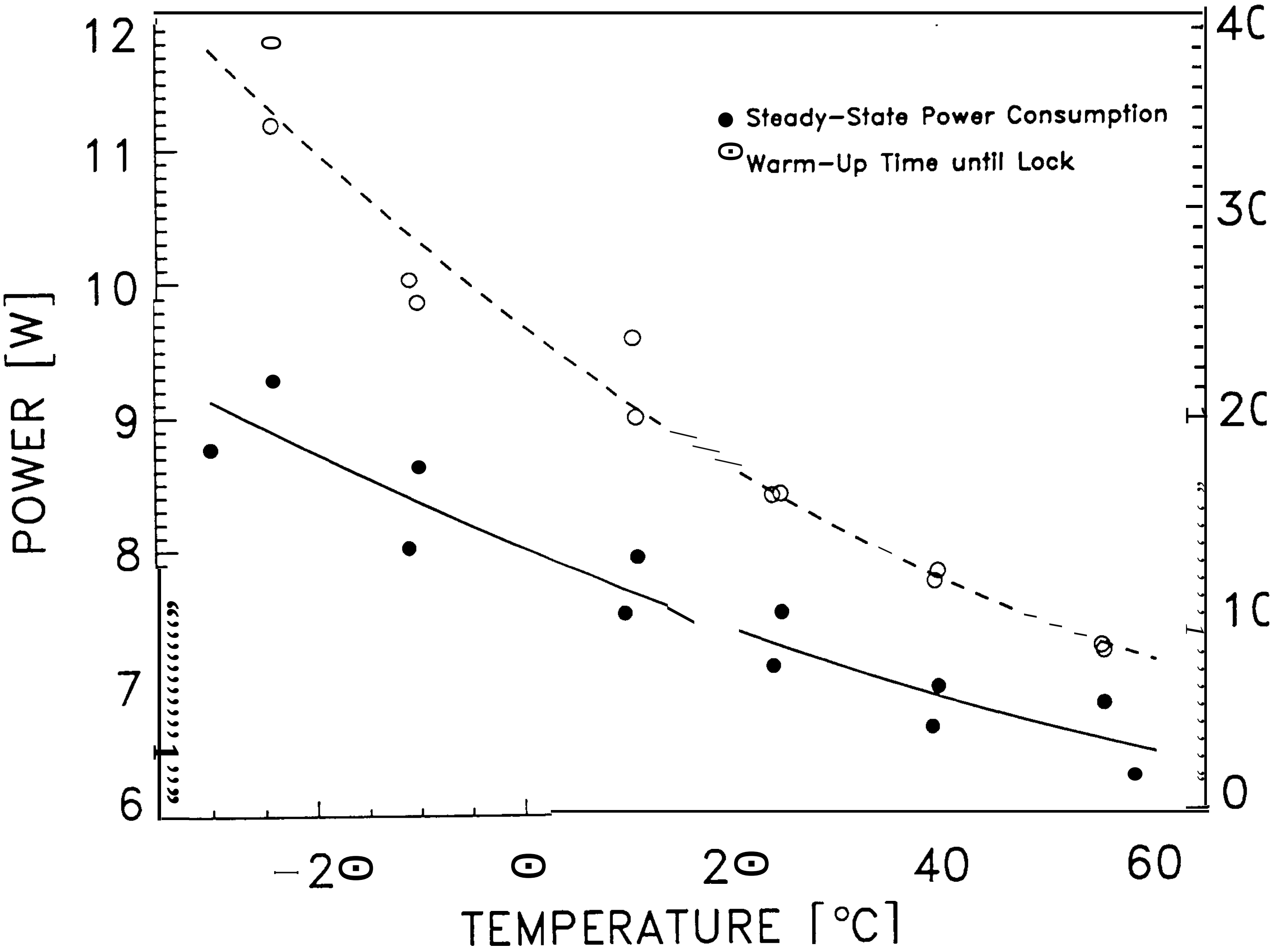

Fig. 3. DWE-USO steady-state power consumption (solid circles) and warm-up time to internal lock (open circles) as a function of ambient temperature. The solid and dashed lines are quadratic least-squares fits to the solid and open circles, respectively.

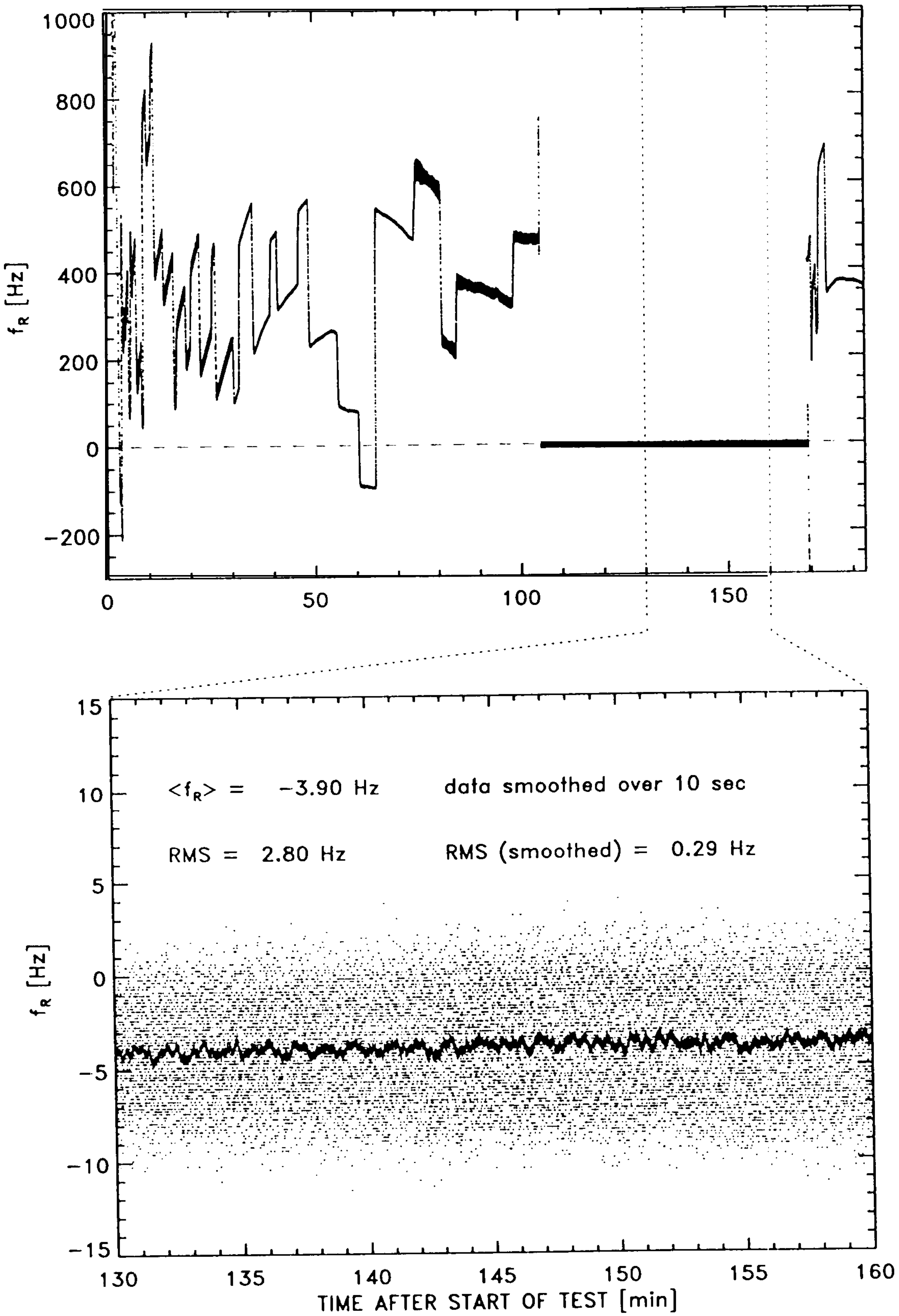

Fig. 4. Frequency measurements of Huygens radio signal during first Integrated System Test. Upper panel: Comparison TCXO vs. TUSO/RUSO. The radio subsystem was driven by ordinary oscillators (TCXOs) until ~104 min. after start, at which time the driver function was switched to the TUSO/RUSO combination. Lower panel: High-resolution plot showing DWE frequency measurement accuracy at integration times of 0.125 s (point cluster) and 10 s (solid line).