Winds on Titan: First results from the Huygens Doppler Wind Experiment

Supplementary Discussion.

It was realized during the DWE design phase that Earth-based Doppler measurements could be combined with the orbiter Doppler measurements to reconstruct both the zonal and meridional components of the Huygens probe motion during descent. Ideally, the horizontal projections of the Huygens-to-Cassini and Huygens-to-Earth ray paths should be perpendicular for this purpose, but the 160º separation for the actual experiment geometry was considered adequate for the calculation. A fundamental uncertainty in the Earth-based measurement was whether the received power from the Huygens carrier signal would be sufficient to support near real-time reduction of the data, or a more extensive data processing effort, augmented with additional information from the telemetry sub-bands, would be required. This latter procedure was necessary, for example, in the case of the ground-based detection of the Galileo Probe signal at Jupiter (Folkner et al. 1997). In spite of the considerably greater distance, the probability for detecting the Huygens signal from Titan was deemed slightly more favorable than for the case of the Galileo Probe. The primary factors leading to this conclusion were the considerably higher Huygens transmitter antenna gain toward Earth as well as the presence of significant residual carrier power in the Huygens signal as opposed to no residual carrier for the Galileo Probe. As a result, preparations were undertaken to establish an Earth-based network of radio telescopes that would record the frequency of the Huygens Ch. A signal during the Titan descent. Two essential telescope selection criteria were: (a) capability of receiving the Huygens 2040 MHz signal, and (b) sufficient elevation above the local horizon for visibility of Titan during the Huygens mission.

A second Earth-based experiment designed to provide ultra-precise sky positions of the Huygens probe using the technique of Very Long Baseline Interferometry (VLBI) was developed over the latter years of the interplanetary cruise phase (Gurvits 2004; Pogrebenko et al. 2004). The results of the VLBI experiment, which enlisted a total of 17 radio telescopes in Australia, China, Japan, and the USA, are to be described elsewhere. Together, the VLBI and Earth-based Doppler experiments constituted the radio astronomy segment of the Huygens mission. A joint observation proposal was submitted to the National Radio Astronomy Observatory (NRAO), specifically for observation time at the Robert C. Byrd Green Bank Telescope (GBT) in West Virginia, and at eight antennas of the Very Long Baseline Array (VLBA), and to the Australia Telescope National Facility (ATNF) for observations at the Parkes Radio Telescope and several other smaller Australian antennas.

Six of the 17 radio telescopes participating in the radio astronomy segment of the Huygens mission conducted Earth-based DWE measurements of the received frequency, which, owing to the loss of Ch. A on Cassini, thus comprise the DWE data base. Supplementary Table 1 lists the six Earth-based DWE stations and their respective observation intervals in terms of Earth received time (ERT/UTC). The corresponding time at Huygens, the Spacecraft Event Time (SCET/UTC), is obtained by subtracting the one-way light time of ~4026.35 s ($1^{h}\ 7^{m}\ 6.35^{s}$). Special NASA Deep Space Network Radio-Science Receivers (RSRs), designed to support and display radiometric recording of extremely narrowband spacecraft signals, were installed for this unique occasion at GBT and Parkes. Even for the GBT, the largest available radio telescope for this purpose, link budget calculations of the Huygens signal strength predicted a voltage signal-to-noise ratio of about 3:1 using only the probe carrier signal (see Supplementary Table 2). Four stations from the VLBA network were also equipped to record the Huygens signal pass-band for Doppler analysis. Only the GBT and Parkes RSR data sets are discussed in this initial report.

The topocentric sky frequency of the Huygens Ch. A carrier signal recorded at GBT and Parkes is shown in Supplementary Figures 1-3. Reflecting the velocity and pointing direction of the specific receiving antenna, this is the frequency actually observed at each ground station. The time resolution is typically one point each 10 seconds, for which the measurement error is of the order of 1 Hz, corresponding to an uncertainty in the line-of-sight velocity of 15 cm/s. Supplementary Figure 1 shows all data from both facilities, while Supplementary Figures 2 and 3 display higher time resolution data plots recorded at GBT and Parkes, respectively. The Earth-based signal detection at GBT coincides with the initial transmission from Huygens at t_0 + 45 s, where t_0 is the designated start of the descent at 09:10:20.76 SCET/UTC.

The small gaps in the GBT and Parkes measurements occur when the telescope pointing direction was offset from Huygens to observe a nearby natural radio source for purposes of calibrating the Huygens VLBI experiment. This observation cycle was repeated every three minutes, of which about 100 s were allocated to direct tracking of Huygens. A single larger gap of 26 minutes is present in the interval between the end of the observations at GBT and the start of observations at Parkes. It is anticipated that this gap will be filled largely with Doppler data from the four VLBA stations. Furthermore, since two VLBA stations, Pie Town and Owens Valley, did not participate in the VLBI antenna nodding procedure (Supplementary Table 1), it may be possible to fill the gaps within the GBT and Parkes observation intervals. Doppler measurements extracted from the VLBI recordings at GBT and Parkes have been found to be in excellent agreement (differences typically less than 1 Hz) with the RSR data.

The Doppler shift of the Huygens signal is determined primarily by the relative velocity of Titan and Earth. The difference in telescope velocity toward Titan due to Earth's rotation is reflected in the frequency offset between that seen toward the end of track at GBT and that seen at the start of track at Parkes (Supplementary Figure 1).

Predictions of the received frequency are included in Supplementary Figures 2 and 3. These were derived from simulations of the Huygens motion during the atmospheric descent in the absence of wind (dotted curve) and with a standard project engineering wind model (solid line). This latter wind model (Flasar et al. 1997) features a purely zonal prograde flow, i.e., in the direction of Titan's rotation, that increases linearly from zero at the surface to 100 m/s at a height of 160 km. The meridional flow is zero in these models. Noting that many of the GBT Doppler measurements roughly follow intermediate values between the prediction without wind and the prediction with a prograde wind (Supplementary Figure 2), it is apparent that the probe must have been drifting for much of the descent in the same direction as that predicted by the project engineering model, but with a slower line-of-sight velocity.

References to Supplemental Information

Flasar, F.M., Allison, M. & Lunine, J.I. Titan zonal wind model. in *Huygens Science Payload and Mission*, ESA-SP 1177, 287-298 (1997).

Folkner, W.M. et al. Earth-based radio tracking of the Galileo Probe for Jupiter wind estimation. *Science* **275**, 644-646 (1997).

Gurvits, L.I. Christiaan Huygens, Huygens the probe and radio astronomy. in *Titan: from Discovery to Encounter*, ESA-SP 1278, 408-411 (2004).

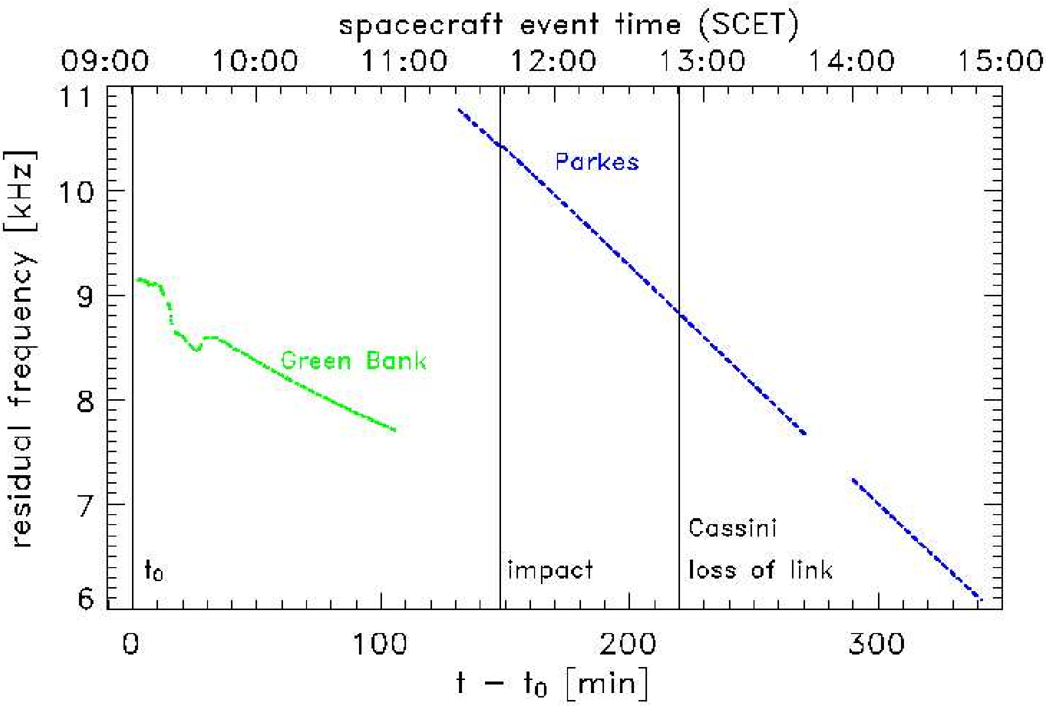
Pogrebenko, S.V. et al. VLBI tracking of the Huygens probe in the atmosphere of Titan. in *Planetary Probe Atmospheric Entry and Descent Trajectory Analysis and Science*, ESA-SP 544, 197-204 (2004).

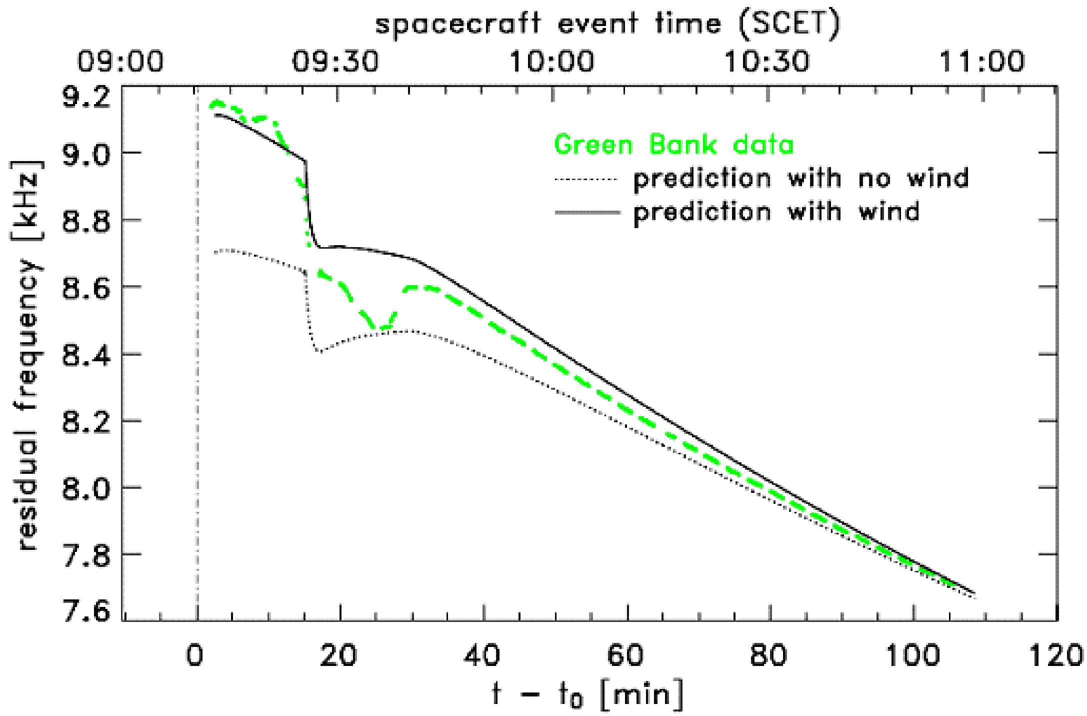
Figure Captions – Supplementary Information

Supplementary Figure 1. Topocentric sky frequencies of the Huygens Ch. A carrier signal recorded at the GBT and Parkes facilities. The nominal transmit frequency (a constant value of 2040 MHz) has been subtracted, so that the plotted data points are equivalent to the total signal Doppler shift from transmitter to receiver. The upper time scale is Spacecraft Event Time; the lower scale is minutes past the nominal start of mission at t_0 = 09:10:20.76 SCET/UTC. The Earth's rotation is primarily responsible for the lower recorded frequency at GBT (near end of track) with respect to Parkes (near start of track). The small gaps between data segments correspond to intervals when the radio telescopes were pointed to celestial reference sources near Titan for calibration of the simultaneously conducted VLBI experiment. The times of impact at t_0 + 147 m 50 s, (11:38:11 SCET/UTC) and loss of link to Cassini at t_0 + 220 m 3 s (12:50:24 SCET/UTC) are indicated. The Parkes tracking pass ended at t_0 + 341 m 37 s (14:51:58 SCET/UTC) with the Huygens probe still transmitting from the Titan surface.

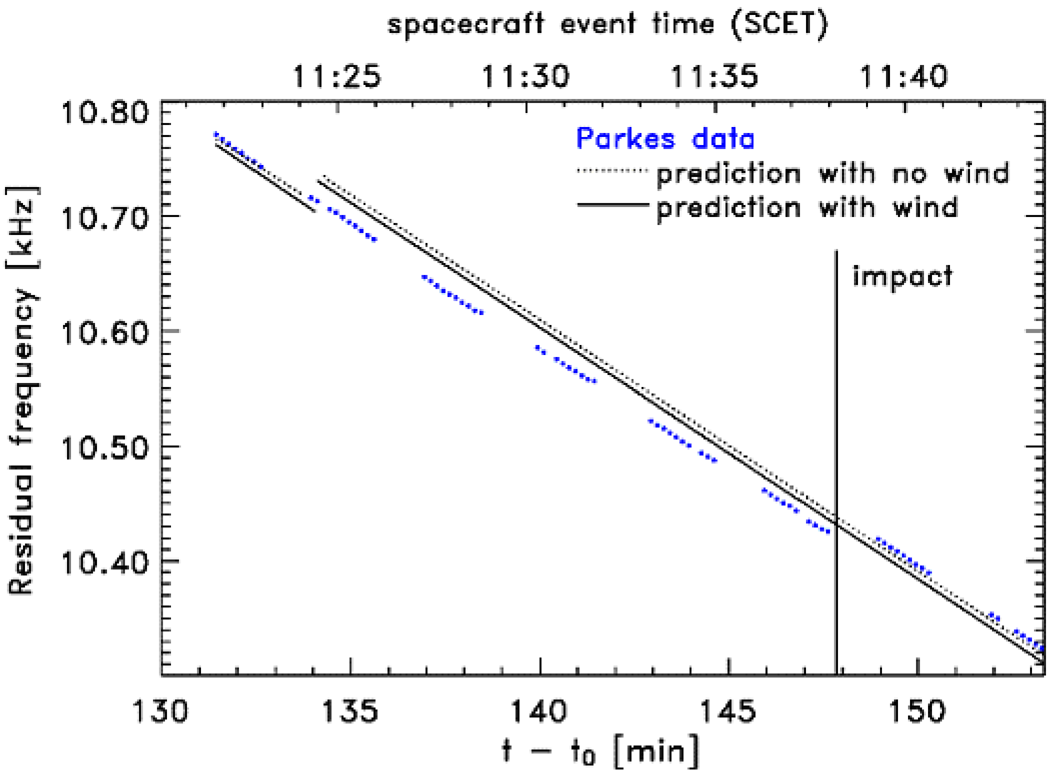
Supplementary Figure 2. GBT frequency measurements from the start of the Huygens broadcast until end of track. The recorded data (dots) generally lie between the predicted Doppler values assuming no winds (thin dotted curve) and a model with a moderate prograde wind (thin curve). A clear Doppler signature for the change from the main parachute to a smaller drogue parachute may be seen at t_0 + 15 minutes. At this instant, the suddenly larger descent velocity produces an abrupt decrease in the received frequency which closely follows that predicted by simulation.

Supplementary Figure 3. Parkes frequency measurements near the time of surface impact. Actual observations (dots) are compared with predictions with wind (thin curve) and no wind (thin dotted curve), respectively. The obvious discontinuities in the prediction curves result from the simulated impact on Titan at ~11:24 SCET/UTC for this specific model. The actual impact at 11:38:11 SCET/UTC occurred during one of the small data gaps when the Parkes antenna was pointed away from Huygens. The nearly discontinuous increase in frequency at 11:38:11 SCET/UTC marks the impact on the surface. The magnitude of this positive jump in frequency, 26.4±0.5 Hz, reflects the abrupt change in vertical velocity from about 5 m/s to zero.





spacecraft event time (SCET)
09:00
09:30
10:00
10:30
11:00
9.2
9.0
8.8
8.6
8.4
8.2
8.0
7.8
7.6
residual frequency [kHz]
Green Bank data
prediction with no wind
prediction with wind
0
20
40
60
80
100
120
t − t0 [min]



spacecraft event time (SCET)
11:25
11:30
11:35
11:40
10.80
10.70
10.60
10.50
10.40
Residual frequency [kHz]
Parkes data
prediction with no wind
prediction with wind
impact
130
135
140
145
150
t − t0 [min]

Supplementary Table 1 Radio telescopes in Earth-based DWE Network

Facility	Diameter (m)	Latitude (deg)	West Longitude (deg)	Start (UTC)	Stop (UTC)	Notes
GBT	100	38.4	79.8	09:31:10	12:15:00	1,2
VLBA Pie Town	25	34.3	108.1	09:30:11	14:15:04	3
VLBA Kitt Peak	25	32.0	111.6	09:31:10	14:15:00	2
VLBA Owens Valley	25	37.2	118.3	09:30:09	14:49:14	3
VLBA Mauna Kea	25	19.8	155.5	09:31:10	16:00:00	2
Parkes	64	-33.0	211.7	12:26:23	16:00:00	1,2

(1) Real time signal detection

(2) Nodding between Huygens and reference

(3) No nodding; continuous Huygens tracking

Supplementary Table 2   Radio Link Budget: Huygens-to-GBT

Transmitter Parameters	
RF Power (dBm)	40.7
Probe Antenna Gain (dBi)	3.5
Losses (dB)	-0.4
Effective Radiated Power (dBm)	43.8
Propagation Space Loss (dB)	-280.5
Receiving Antenna Gain (dBi)	65.0
Power Summary	
Received Power (dBm)	-171.7
Noise Spectral Density (dBm/Hz)	-183.8
Received Pt/N0 (dB Hz)	12.1
Modulation Loss (dB)	-4.5
Received Pc/N0 (dB Hz)	7.6
Voltage SNR at $\tau = 1$s	3.4