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RADIO SCIENCE DOPPLER WIND EXPERIMENT

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Doppler Effect

<u>1842</u>

Named for Austrian mathematician and physicist Christian Doppler who first described the effect.

Doppler attempted to explain the color of binary stars in paper presented at the Royal Bohemian Society "*On the coloured light of the binary stars and some other stars of the heavens*".

Doppler Effect

"The change in the apparent time interval between two events which arises from the motion of an observer together with the finite velocity of information about the events".

- T.P. Gill, *The Doppler Effect* (1965)

Doppler Effect

<u>1710</u>

Danish Astronomer Ole Römer credited with making first measurement of speed of light by measuring the time difference (over a period of six months) between successive eclipses of Io in orbit around Jupiter.

What Römer actually measured was a Doppler effect - the change in apparent difference in time of Io eclipses due to the motion of the Earth around the sun.

Doppler Effect – Simple Theory

Received frequency f_{rec} due to line of sight (LoS) velocity $v_{\mathrm{LoS}} = \frac{dr}{dt} = \dot{r}$. f_0 is transmitted frequency, and c is the speed of light.

$$f_{rec} = f_0\left(1 - \frac{\dot{r}}{c}\right)$$

Doppler frequency f_{Dopp} is defined as the difference between the transmitted and received frequencies

$$f_{Dopp} = f_{rec} - f_0 = -f_0\frac{\dot{r}}{c}$$

Important note on sign conventions: If distance between source & receiver is

increasing, $\dot{r} > 0$ and $f_{Dopp} < 0$ (red shift, $f_{rec} < f_0$)

decreasing, $\dot{r} < 0$ and $f_{Dopp} > 0$ (blue shift, $f_{rec} > f_0$)

Doppler Effect - Better

A more accurate formulation of the Doppler Effect

$$f_{rec} = f_0 \left(\frac{1}{1 + \frac{\dot{r}}{c}} \right) = f_0 \left(1 + \frac{\dot{r}}{c} \right)^{-1}$$

$$\approx f_0 \left(1 - \frac{\dot{r}}{c} \right) \qquad \dot{r} \ll c$$

$$f_{Dopp} = f_{rec} - f_0 = -f_0 \frac{\dot{r}}{c}$$

Doppler Effect - Best

$$f_{rec} = f_0 \frac{\sqrt{1 - \frac{v_{tot}^2}{c^2}}}{1 + \frac{\dot{r}}{c}}$$

$\dot{r}$ is rate at which the distance between the transmitter and the receiver is changing (Line of Sight velocity).

v_{tot} is the <u>total</u> transmitter velocity in the frame in which the receiver is at rest.

Note that this formulation accounts for the *time dilation* effect of special relativity (often incorrectly called the <u>transverse Doppler Effect</u>).

<u>Example</u> If transmitter is in circular orbit around receiver with speed v_{tot}, then distance between transmitter and receiver does not change, $\dot{r}$ is zero, and proper Doppler Effect is zero.

However, due to time dilation effect, there is still a measurable change in received frequency due to “transverse” Doppler shift. This effect is always negative (i.e., red shift, to lower frequencies).

Doppler Effect - Best

Upon expanding and keeping terms to *1/c*^{2} only

$$f_{rec} = f_0\left(1 - \frac{\dot{r}}{c} - \frac{v_{tot}^2}{2c^2} + \frac{\dot{r}^2}{c^2}\right)$$

$$f_{Dopp} = f_{rec} - f_0 = -f_0\left(\frac{\dot{r}}{c} - \frac{\dot{r}^2}{c^2} + \frac{v_{tot}^2}{2c^2}\right)$$

Classical Doppler Effect

Classical Doppler Effect (2nd order)

Transverse Doppler

Important Note

When transmitting through a refracting medium (an atmosphere) the geometrical change in distance $\dot{r}$ is replaced by time derivative of the ray path (phase path length) through the atmosphere.

For most probe missions, the effect of atmospheric refraction on the Doppler profile is negligible. However, it is this phenomenon that allows for the radio occultation technique of studying planetary atmospheres.

Gravitational Redshift

While not a true Doppler effect, changes in gravitational potential between transmitter and receiver often have a non-negligible effect on the signal frequency.

Gravitational Redshift

Assuming weak gravitational field theory (see Landau and Lifshitz, *Classical Theory of Fields*, 1975), the apparent change in frequency of a photon traveling from r_1 to $r_2 > r_1$ in a gravitational potential

$$\Phi = \frac{GM}{r}$$

is

Gravitational Redshift

$$f_{rec} = f_0 \exp\left[\left(\frac{GM}{c^2}\right)\left(\frac{1}{r_2} - \frac{1}{r_1}\right)\right]$$

This effect is non-negligible. For the Galileo probe transmitting to the Galileo orbiter at Jupiter, the gravitational redshift contributed about -20.5 Hz to the Doppler budget.

For the Huygens probe transmitting from Titan to Earth the gravitational redshift contributed +18.9 Hz.

Doppler Wind Experiment Goals

Primary: Retrieve a vertical profile of the horizontal wind structure of the atmosphere along the path of probe descent.

Secondary: Detect and measure atmospheric waves, convection, turbulence, and probe microdynamics (spin, pendulum, and aerodynamic buffeting).

Doppler Wind Experiment

<Most Important Point>

The Doppler Wind Experiment
does not measure wind!

The Doppler Wind Experiment measures probe motion.

It is assumed that the Doppler frequency residuals caused by unmodeled probe motion reflects the dynamics of the atmosphere.

Doppler Wind Experiment

The probe/parachute system has mass = inertia and therefore does not respond instantaneously to changes in wind speed.

Doppler Wind Experiment

A simple, first order calculation shows that a probe in terminal descent under a parachute will respond to an instantaneous wind gust in a time T (seconds)

$$T = V_{descent}/g$$

where g is the local acceleration of gravity, m/s^2.

A probe can therefore detect changes in wind speed over atmospheric layers of thickness L (meters)

$$L = V_{descent}*T = V^2_{descent}/g$$

Doppler Wind Measurement on Mars

- Difficult due to thin atmosphere on Mars.
- Viking 1 and 2 Landers under parachute for ~62 seconds.
- Viking 1 terminal descent started at altitude of 3.3 km and ended with firing of landing rockets at 1.5 km.
- Descent speed under parachute ~55 m/s, Mars gravity $g = 3.73\ m/s^2$

$$T = \frac{55\ m/s}{3.73\ m/s^2} = 14.7 \text{ seconds}$$

$$L = 55\ m/s * 14.7 \text{ seconds} = 810 \text{ meters}$$

Doppler Wind Measurement on Mars

- During the ~1 minute under parachute, Seiff attempted a wind measurement with Viking Landers 1 and 2 (not using Doppler techniques).
- Viking Lander instruments used for wind reconstruction: inertial reference unit (three-axis accelerometers and gyroscopes), radar altimeter, and Doppler radar.
- After parachute jettison (final 1.5 km), measurement of winds not attempted due to uncharacterized horizontal components of landing rocket forces and unknown aerodynamic forces of winds acting on landers.

References:

Seiff, A. "Mars Atmospheric Winds Indicated by Motion of the Viking Landers During Parachute Descent," J. Geophys. Res., Vol. 98, E4, 7461-7474, April 25, 1993.

Withers, P., R. D. Lorenz, and G. A. Neumann "Comparison of Viking Lander Descent Data and MOLA Topography Reveals Kilometer-Scale Offset in Mars Atmosphere Profiles," Icarus 159, 259–261 (2002).

DWE Background – Basics

If transmitted frequency, all positions and velocities of the probe and receiver, and all other effects are known, then frequency measured at receiver can be reconstructed exactly.

Doppler residuals represent excess frequency that is assumed to be due to unmodeled probe motions.

Assuming that probe descent speed is well known, Doppler residuals represent unmodeled errors in probe to receiver range rate (range rate residuals, m/s). The zonal winds result from the projection of the range rate residuals onto the local horizontal at the probe.

DWE Background – Simple Theory

Doppler Residual $$\Delta f_{Dopp} = -\frac{f_0}{c}\delta v_{LoS} = -\frac{f_0}{c}\vec{v}_{zonal}\cdot\hat{n}_{LoS}$$

where $\vec{v}_{zonal}$ is the zonal wind speed, and $\hat{n}_{LoS}$ is the unit vector from the probe to the receiver. The LoS velocity residual δv_{LoS} is

$$\delta v_{LoS} = \frac{\partial v_{LoS}}{\partial \dot{\phi}}\delta\dot{\phi} + \frac{\partial v_{LoS}}{\partial \phi}\delta\phi$$

ϕ = East-West (zonal) angular position (longitude) of probe.

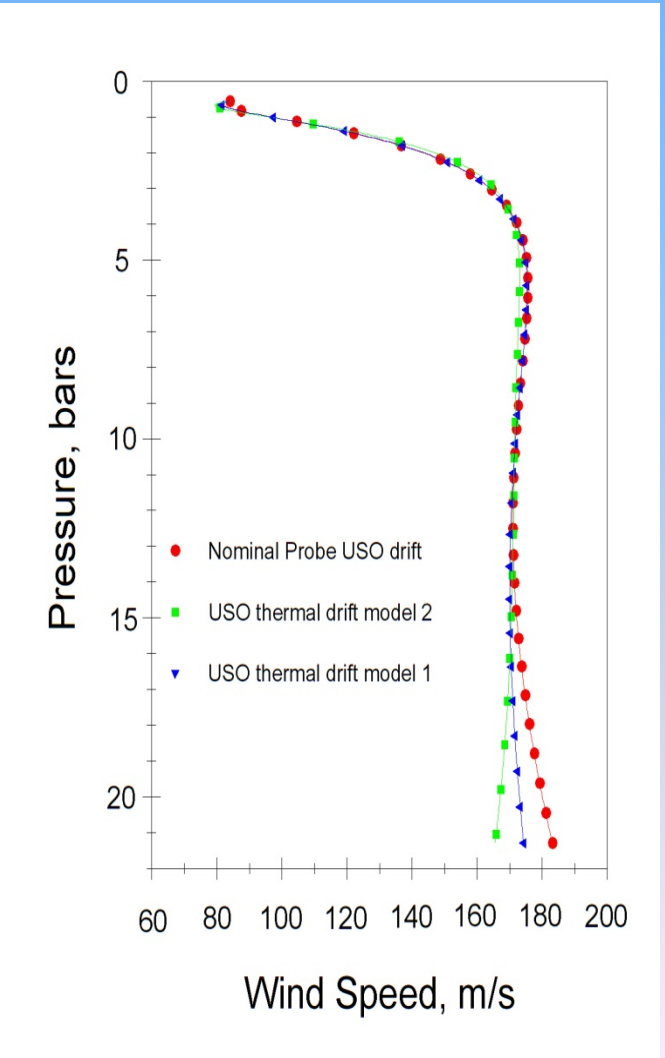
$\delta\dot{\phi}$ = change in zonal motion of probe due to winds.

$\delta\phi$ = change in probe longitude due to integrated effect of winds.

Doppler Wind Heritage

Type I DWE: Giant Planets, Rapidly Changing Geometry

- Galileo / Jupiter, 1995
- Probe horizontal traverse due to winds significantly larger than vertical descent under parachute.
- Probe longitude delivery error of .07 degree → Doppler equivalent of 300 m/s zonal wind (due to rapid rotation of Jupiter).
- Integrated effect of wind on probe longitude caused a Doppler contribution > 250 Hz, equivalent to 310 m/s zonal wind.



Doppler Wind Heritage

Type I DWE: Giant Planets, Rapidly Changing Geometry

- Algorithm developed uses difference in Doppler frequencies to remove (to 1st order) effect of probe descent longitude uncertainties.
- However, absolute winds can still be measured.
- LoS velocity from winds is due to instantaneous zonal winds V_Z and geometrical projection factor G. The change in LoS velocity due to winds is

$$\Delta V_{LoS} = \Delta V_Z * G + V_Z * \Delta G$$

Doppler Wind Heritage

$$\Delta V_{LoS} = \Delta V_Z * G + V_Z * \Delta G$$

The change in Doppler is proportional to the change in LoS velocity due to 1) geometry and change in zonal winds, <u>and</u> 2) the absolute winds and the change in geometry.

If the geometry changes substantially during the probe descent, differences in Doppler frequency can still provide an absolute wind profile.

Value of using differences in Doppler frequency is that (to 1st order) the resulting wind measurement is independent of initial uncertainties in probe longitude and transmitted frequency.

Important Note

Additional complication in Type I DWE retrieval is that algorithm must account for both instantaneous effect of winds as well as integrated effect of winds on probe descent location.

$\dot{r}$ is probe-receiver range rate, m/s (- sign omitted)

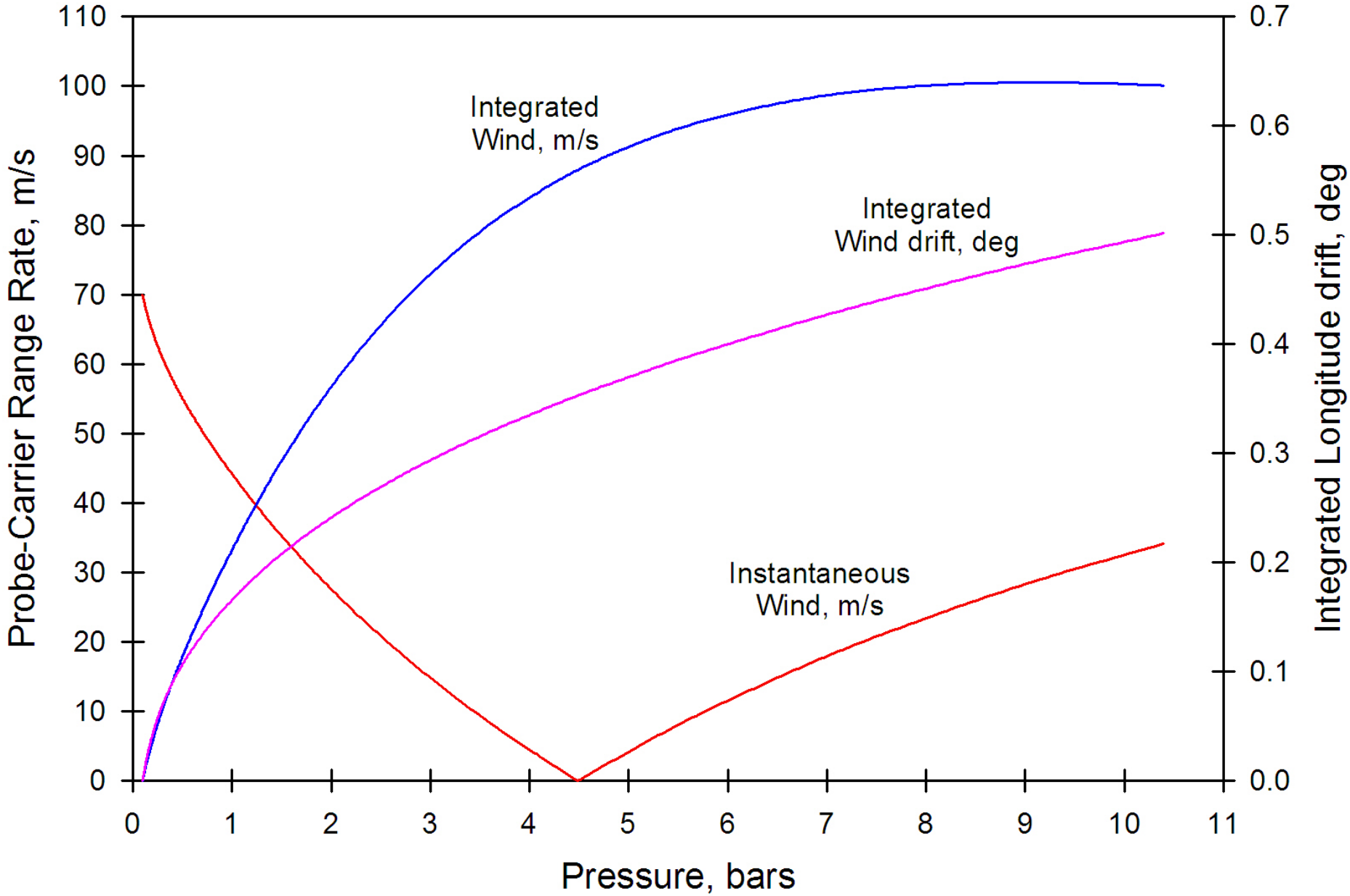
$$f_{Dopp} = \frac{f_0}{c}\dot{r} = \frac{f_0}{c}\frac{\partial \dot{r}}{\partial V_z}\delta V_z + \frac{f_0}{c}\frac{\partial \dot{r}}{\partial \varphi_p}\delta\varphi_p$$

Instantaneous wind effect, V_z

Integrated wind effect

Instantaneous zonal winds V_z

Integrated change in probe longitude φ_p due to zonal winds


Probe-Carrier Range Rate, m/s
Integrated Longitude drift, deg
Pressure, bars
Integrated
Wind, m/s
Integrated
Wind drift, deg
Instantaneous
Wind, m/s
0
10
20
30
40
50
60
70
80
90
100
110
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0
1
2
3
4
5
6
7
8
9
10
11

Doppler Sensitivities – Galileo/Jupiter

Galileo probe link frequency: 1387 MHz

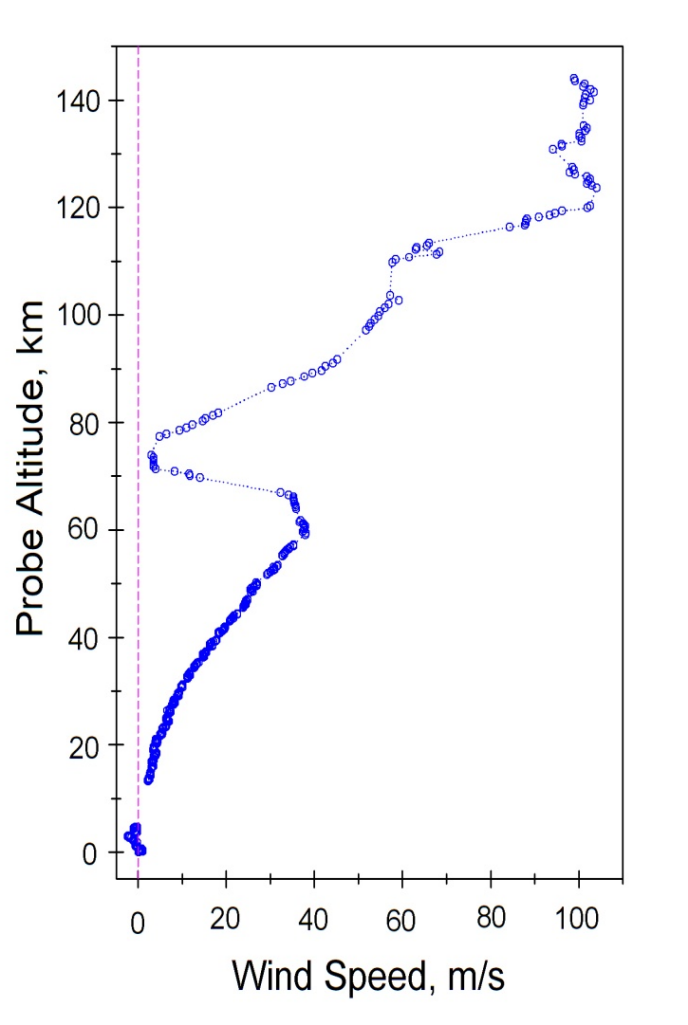
	Partial Derivative	Freq, Hz	Zonal Wind Equiv, m/s
1 m/s merid wind	dV_{LOS}/dV_{merid} = .026 m/s / m/s	0.12 Hz	.298 m/s
1 m/s zonal wind	dV_{LOS}/dV_{zonal} = .087 m/s / ms	0.40 Hz	1.00m/s
1 m/s desc speed	dV_{LOS}/dV_{desc} = .99 m/s / m/s	4.58 Hz	11.36 m/s
1 deg probe long	dV_{LOS}/dPLong = 115.82 m/s / deg	535.47 Hz	1328.89 m/s
1 deg probe lat	dV_{LOS}/dPLat = 4.26 m/s / deg	19.70 Hz	48.89 m/s
1 km probe rad	dV_{LOS}/dPrad = .008 m/s / km	.037 Hz	.092 m/s

Equivalent Zonal Wind speed calculated for probe aspect angle of 5 degrees (orbiter located at 5 degrees off probe local zenith)

Doppler Wind Heritage

Type II DWE: Titan/Venus (Slowly Changing Geometry)

- Huygens, 2005
  - Probe → Cassini orbiter link failed. Earth receivers (Green Bank, WV & Parkes, Australia) picked up Huygens signal.
  - Propagation delay: Earth = 67^{min} as compared to Huygens → Orbiter = 0.2^{s}.
- Integrated Winds
  - Effect of wind on probe longitude caused a zonal drift of approximately 3.56 deg → f_{Dopp}= 16.6 Hz; Equivalent to 4.2 m/s zonal wind.



Doppler Budget – Huygens/Titan

Transmitted frequency = 2040 Mhz. All data at time of first Doppler, altitude = 144 km.

	Range Rate (m/s)	Doppler (Hz)
Receiver Traj (Earth)	-1323.52 m/s	9006.2 Hz
Probe Vertical Descent	41.16 m/s	-280.10 Hz
Zonal Winds (98.42 m/s)	-57.46 m/s	390.97 Hz
Total Doppler	-1339.82 m/s	9117.07 Hz

Other Effects

	Frequency (Hz)	Zonal Wind Equivalent
Gravitational Redshift (Titan to Earth, Sun dominates)	18.88 Hz	4.75 m/s
Transverse Doppler	-7.40 Hz	1.86 m/s
Higher Order Doppler	0.041 Hz	.01 m/s

Doppler Sensitivities – Huygens/Titan

Transmitted frequency = 2040 Mhz. All data at time of first Doppler, altitude = 144 km.

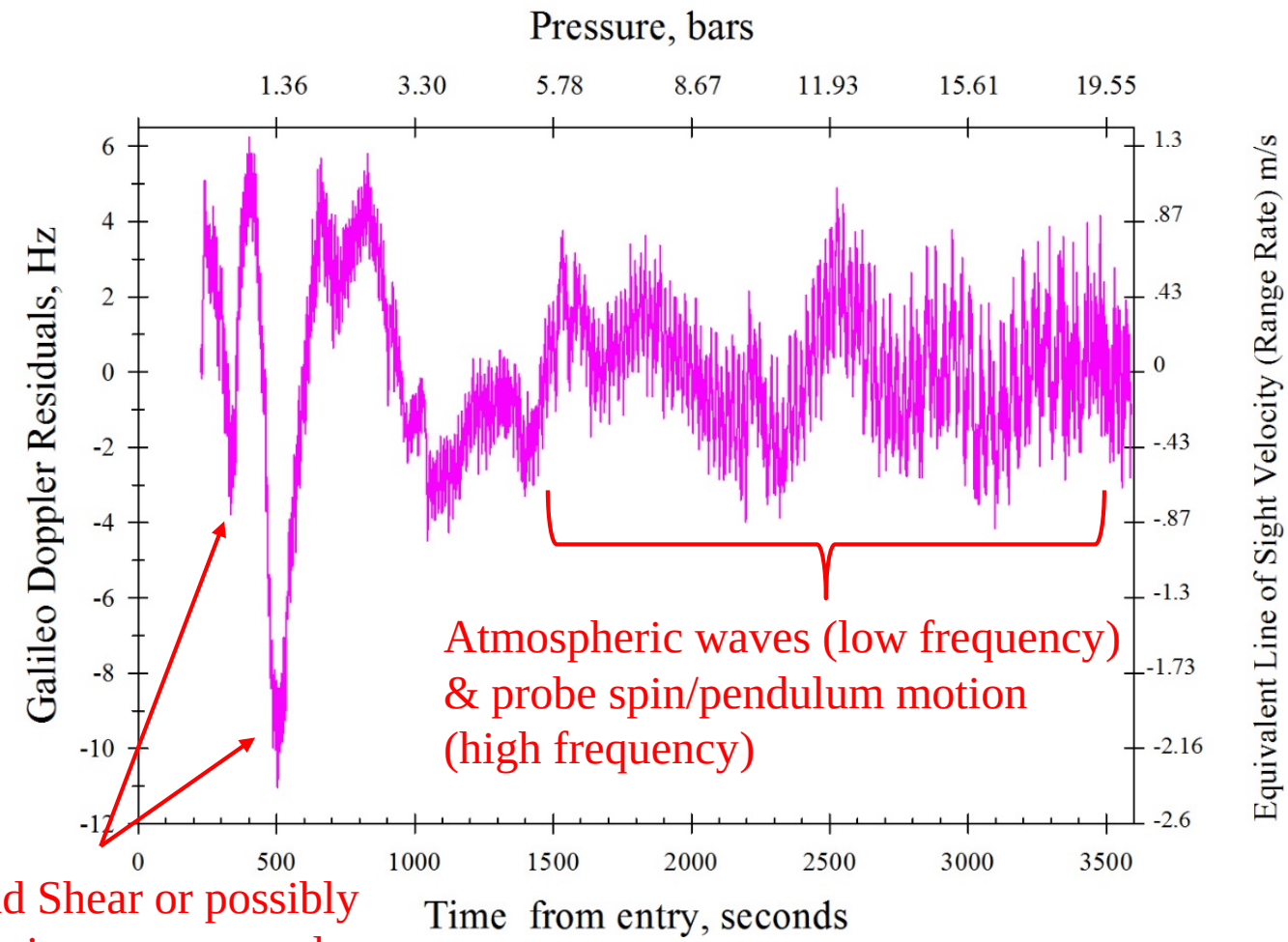
	Partial Derivative	Freq, Hz	Zonal Wind Equiv, m/s
1 m/s merid wind	dV_{LOS}/dV_{merid} = .246 m/s / m/s	1.67 Hz	0.42 m/s
1 m/s zonal wind	dV_{LOS}/dV_{zonal} = .584 m/s / m/s	3.96 Hz	1.0 m/s
1 m/s desc speed	dV_{LOS}/dV_{desc} = .774 m/s / m/s	5.27 Hz	1.33 m/s
1 deg probe long	dV_{LOS}/dPLong = .693 m/s / deg	4.40 Hz	1.11 m/s
1 deg probe lat	dV_{LOS}/dPLat = .252 m/s / deg	1.60 Hz	0.40 m/s
1 km probe rad	dV_{LOS}/dPrad = 0.003 m/s / km	0.02 Hz	.005 m/s

Other Contributions to Doppler Budget

- Probe microdynamics - Spin, Pendulum
- Atmospheric Waves
- Turbulence
- Aerodynamic buffeting

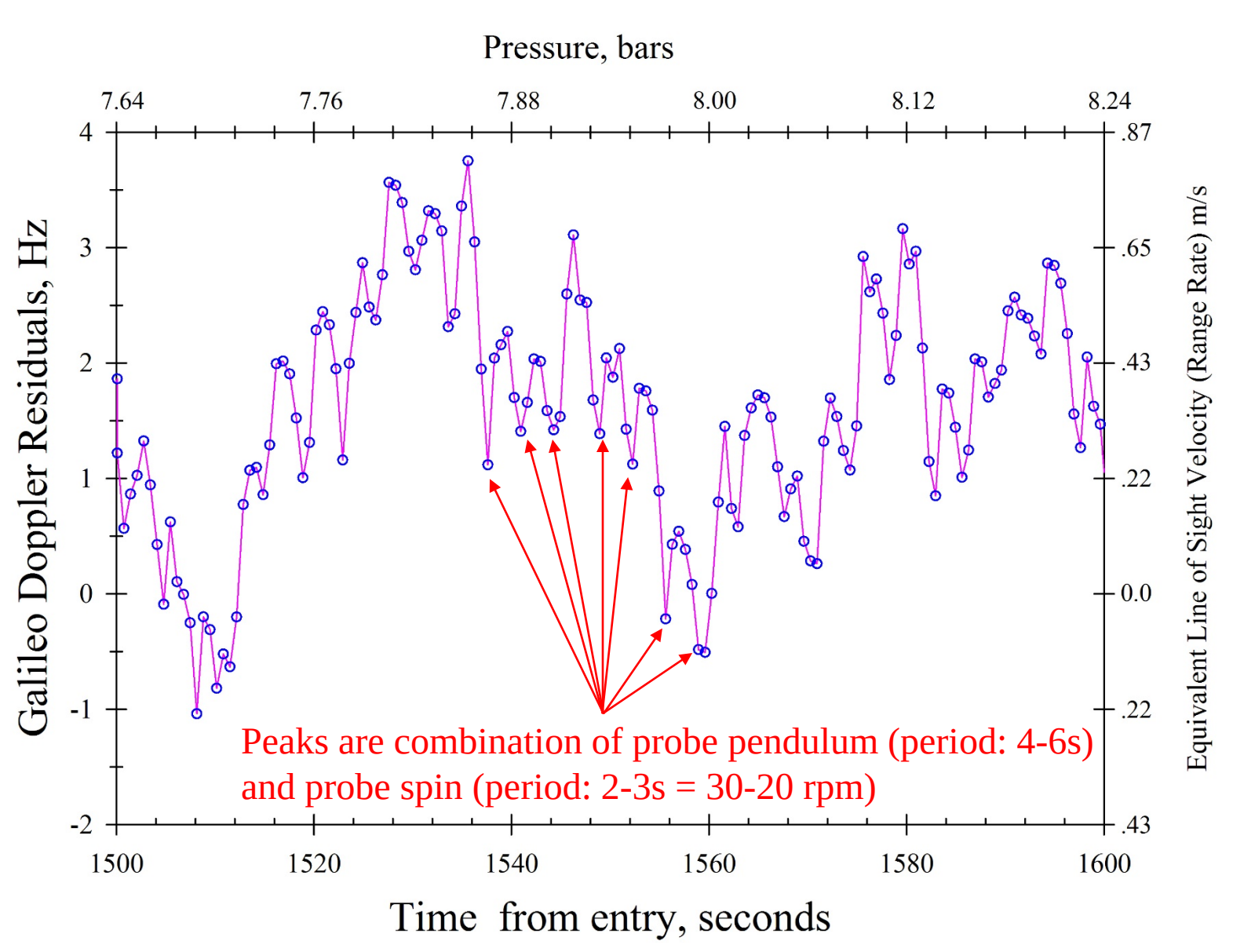
Galileo Probe Doppler Residuals

(after wind retrieval)

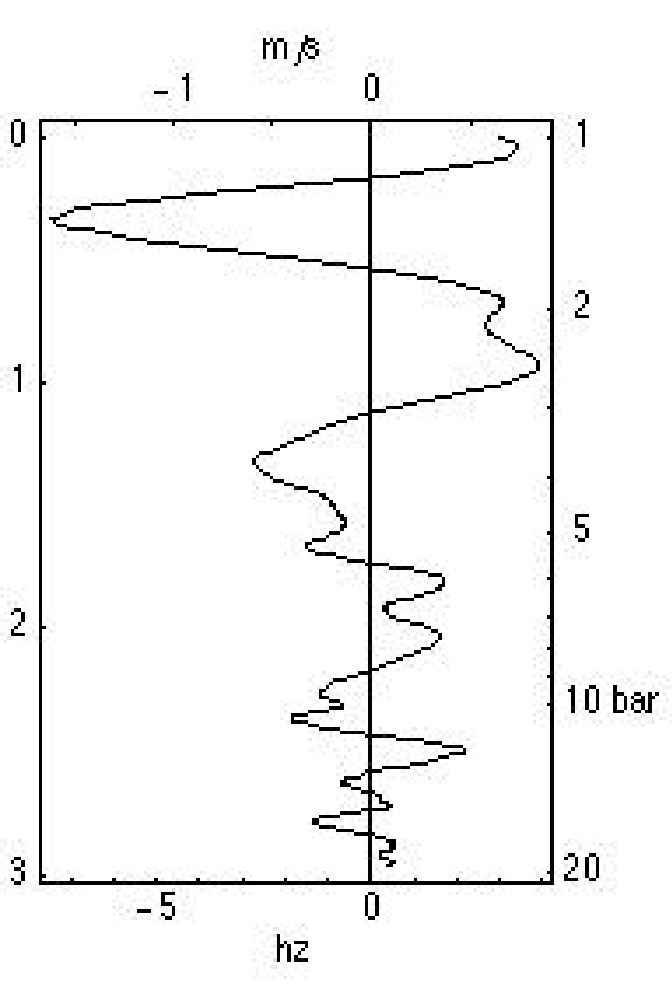


Wind Shear or possibly error in reconstructed probe descent speed

Galileo Probe Doppler Residuals



Doppler Residuals



Filtered Galileo probe Doppler residuals in Hz plotted vs. Log(Press).

Equivalent vertical velocity in m/s at top. Pressure scale heights below 1 bar marked on left.

Downward bunching & substantially decreased amplitudes for oscillations below the ~ 5 bar level is interpreted as a vertically propagating wave implying a downward increasing static stability.

Allison and Atkinson, Geophys. Res. Ltrs., Vol. 28, No. 14, 2747-2750, July 15, 2001

Cost and impact of Doppler wind measurements on spacecraft communication system design

DWE Instrumentation

Stable frequency references needed for accurate measurement of wind-induced Doppler shifts.

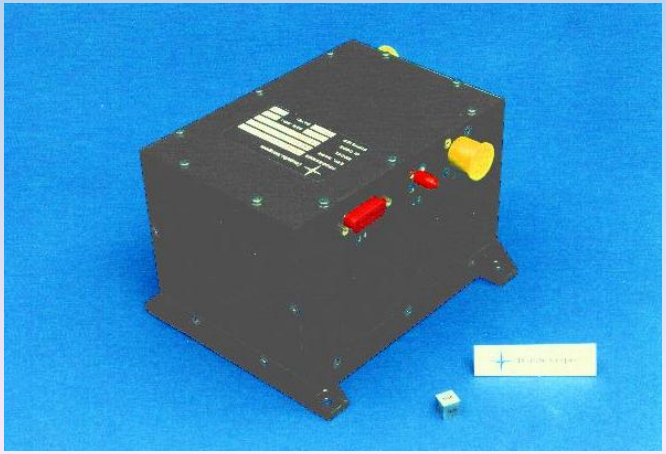
Ultrastable Oscillator (USO) required on <u>both</u> sides of radio link: transmitter (probe) and receiver.

Quartz vs. Rubidium

Galileo Probe USO

Quartz Xtal, Very Stable
Allan Variance (100-s): ~1e-12
Not Accurate: ~500 Hz error
Steady State Power: 2.2 Watts
Mass: 1.1 kg

Huygens Probe USO



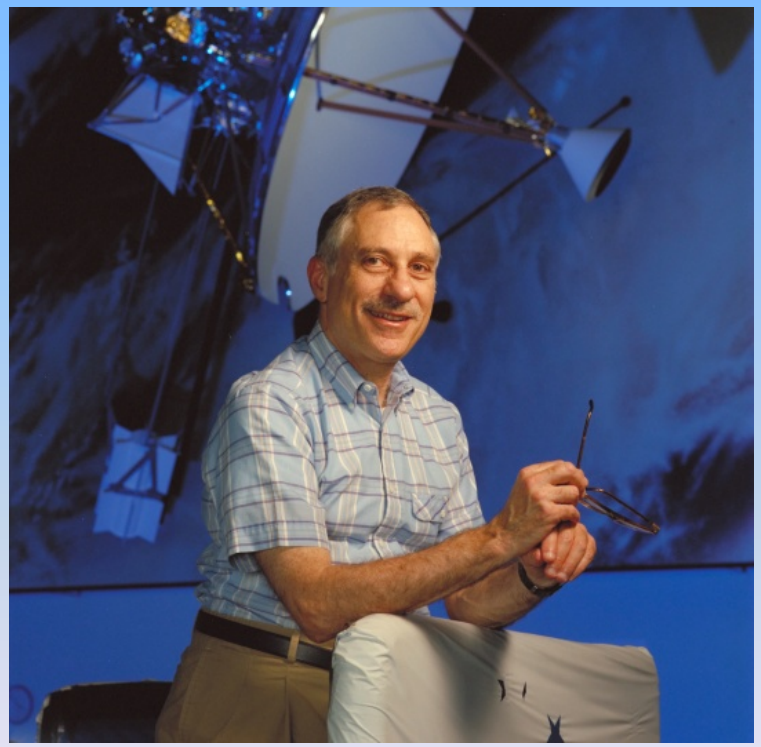
Rb, Very Accurate
Not Stable, Allan Var. (100-s): ~1e-10
Warmup power: 18.4 watts for 20 min
Steady State power: 7.8 watts
Mass: 1.9 kg

Summary and Conclusions

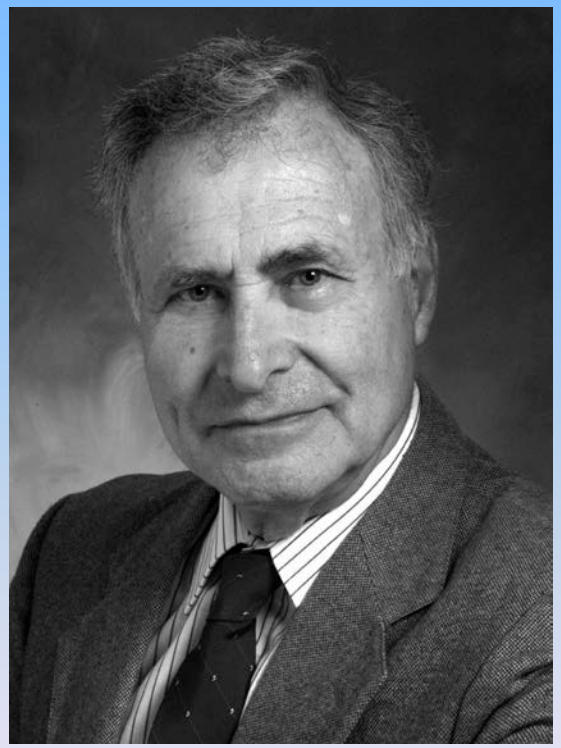
- In situ measurements of planetary atmospheric dynamics are possible if the descent probe and the receiver both are equipped with ultrastable oscillators, and with the design of a reasonable overflight trajectory.
- The total cost of a Doppler Wind Experiment is significantly less than the cost of most instruments comprising the probe science payload.
- The Doppler Wind Experiment can significantly enhance total mission science return for relatively small impact on mission resources (cost, mass and power) and mission design.

Acknowledgements

Many people contributed to the development of the Doppler Wind techniques. Of particular note -



Dr. James B. Pollack



Al Seiff

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