USING SPEED OF SOUND MEASUREMENTS TO CONSTRAIN THE HUYGENS PROBE DESCENT PROFILE

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ABSTRACT

The Acoustic Properties Investigation (API) is a set of sensors for acoustic measurements in gases or liquids, making a part of the Surface Science Package (SSP) on the Huygens probe. It consists of two units, API-V (Velocity of sound) and API-S (Sounding). The API-V has two ultrasonic transducers sending and receiving acoustic pulses over an unobstructed path of 15 cm. An accurate timing circuit is measuring the time it takes to propagate over the distance. Measurements are made in both directions to eliminate the effect of a constant drift of the medium. The transducers have been optimised to operate at low pressure (high altitude) and will operate from about 60km down to the surface. They will also perform well in case of landing in a liquid. The API-S unit is an acoustic sounder, sending short pulses at 15kHz every second and listening for echoes in between. It will detect droplets in the atmosphere and for the last 100m it will characterise the acoustic scattering properties of the surface below. It will also give an accurate value for the descend velocity during the last 100m. In case of landing in a (liquid) lake/ocean it will measure the depth of the lake/ocean down to a maximum of about 1000m.

Accurate measurements of the velocity of sound will, together with knowledge on the temperature, enable the mean molecular weight to be calculated along the descent trajectory. The temperature will be measured by complementary sensors inside the SSP Top Hat, near the API-V, and to a high accuracy by the HASI instrument at the periphery of the Huygens probe.

The API units and associated electronics has been designed and build at the Research and Scientific Support Department at ESTEC, where also the testing and initial calibration has been done. Detailed calibration has been performed with different gas mixtures and at different temperatures in the Titan simulation chamber at the University of Kent, Canterbury, UK. Further supporting studies are planned in the new Titan simulation chamber at the Open University, Milton Keynes, UK.

This paper discusses the hardware, the modes of operation, the calibration and the expected performances, including error sources, measurement accuracy and range of operation.

1. BACKGROUND

The acoustic properties of the atmosphere have been studied since at least the time of Galileo, but detailed records are fairly sparse. The early work was concentrating mostly on speed of sound measurements under different conditions and later studies of sound absorption were included. Perhaps the first study of back scattered sound, with a device somewhat resembling a SODAR (SOund Detection And Ranging), was the experiment of the Irishman John Tyndall 1875. He used a foghorn as transmitter and a 'manual' receiver, i.e. a person listening through a sound collecting horn as shown inn Fig. 1. In this way wind fields and thermal discontinuities were studied [1]. After the pioneering work of Tyndall very little was done in the field of active sounding. Apart from a few studies during the WWII and the end of 1950s it took until the end of the 1960s to take up and further develop the field of active acoustic sounding.

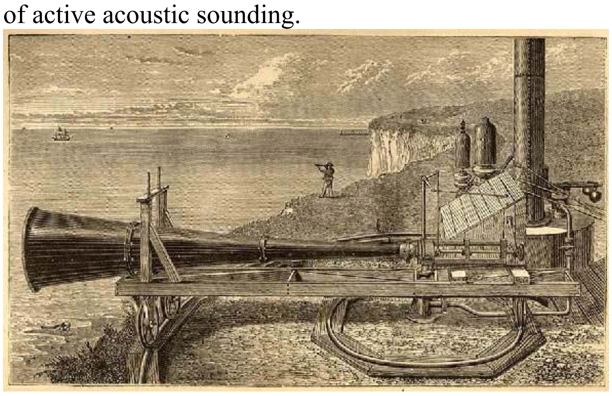

Fig. 1. John Tyndall's atmospheric acoustics experiment 1875 [1].

In space, only the Russian Venera 11 and Venera 12 have carried acoustic sensors. These were basically passive microphones that were brought to Venus for characterising the acoustic environment of the planet and in particular to listen to the thunder associated with the atmospheric lightning that had been proposed earlier. They were calibrated to give information on the local wind speed by detecting the noise generated by turbulence around the spacecraft.

The Acoustic Properties Investigation (API), which is a part of the Surface Science Package (SSP) on the Huygens probe, is one of the most recent developments in active atmospheric acoustics. The purpose of this instrument is to measure the speed of sound in the atmosphere as a function of altitude and to sound the atmosphere for liquid droplets of ethane during the descent through then atmosphere of Titan. We believe that the API/SSP is the first active acoustic instrument outside the earth atmosphere.

1. SCIENCE OBJECTIVES

The primary objectives of the API are the following:

- To measure the speed of sound in the atmosphere as a function of altitude. From the speed of sound the mean molecular weight can be inferred.
- To measure the surface topography for a solid or liquid surface.
- To measure the vertical velocity of the probe. This velocity is related to the density of the atmosphere.
- To measure the speed of sound in the liquid, if landing in a liquid.

The secondary objectives are the following:

- To measure the probe true altitude.
- To measure the direction of the lateral velocity.
- To measure the depth of an eventual ocean.

Also of interest but not yet proven to be feasible are the following points:

- Measurement of eventual surface layering.
- Measurement of the surface acoustic impedance.
- Measurement of the liquid acoustic impedance.
- Measurement of the surface wind speed along the ground track during the descent.
- Measurement of the lateral velocity of the probe. This velocity will be strongly correlated with the horizontal wind speed.

2. INSTRUMENT DESCRIPTION

API has two sets of sensors incorporated into the SSP Top Hat and one card of electronics incorporated in the SSP electronics box. See Fig.2-3.

–API-S, (sounder) is a monostatic SODAR. In the atmospheric mode API-S will detect atmospheric precipitation during the descent. In the near surface mode, during the last phase of the descent, it will characterise the surface and in the surface mode, in case of landing in a liquid, it will detect the depth of this liquid (sea).

–API-V, (velocity) will measure the speed of sound across a 15 cm long path during the descent from an altitude of about 50 km down to the surface, and in the liquid in case of landing in a liquid.

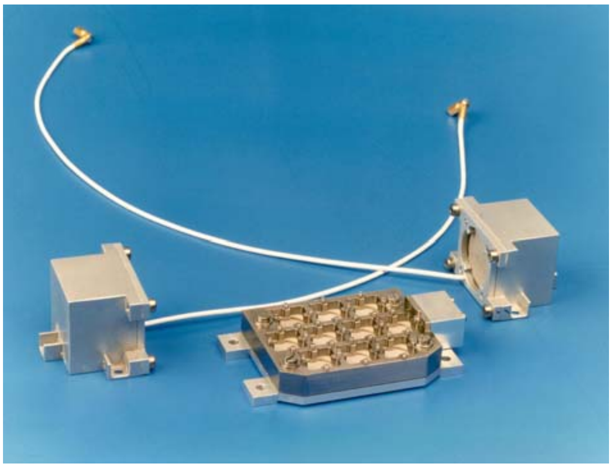

Fig. 2. Development models of the two API-V sensors and the Transmit/Receive transducer for the API-S.

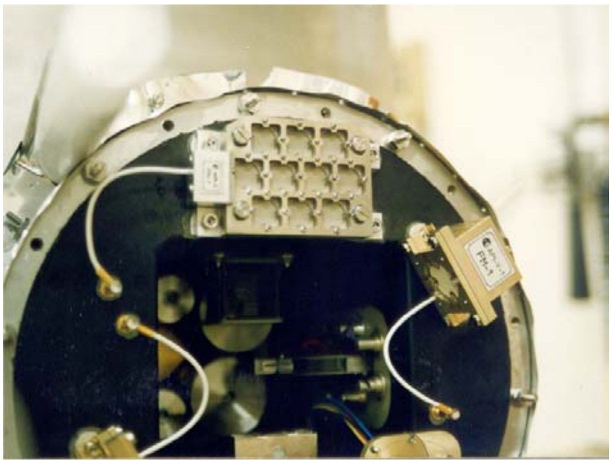

Fig. 3. The SSP Top Hat flight model with the API-V and API-S sensors integrated. The white front of the API-V sensors is a ¼ wavelength thick material with an acoustic impedance in between that of the sensor itself and the atmosphere. This significantly increases the efficiency of the sensors.

The API-S in principle works as a conventional SODAR. It emits an acoustic pulse of a frequency at about 15kHz once per second. In the atmosphere the return signal is proportional to the number density of the scattering particles in the scattering volume and to the particle diameter to the 6th power (Rayleigh scattering). The signal returned from the surface is proportional to the area illuminated by the signal and the surface properties (backscattering coefficient). For both volume scattering and surface scattering the signal is inversely proportional to the square of the distance. The similarities to Electromagnetic Radars are striking. By coincidence the wavelength of the API-S and the Huygens probe Radar Altimeter are both about 2 cm. Comparison of the results from these two systems will therefore be very useful.

3.1 API-S Modes

The API-S will operate in four different modes, depending on the altitude above the surface of Titan.

- Atmospheric sounding mode, h>7km. Search for hydrometeors and turbulence. Pulse length 10 ms. Binned samples for the closes 50 m are stored each 2 seconds.
- Surface proximity mode, 7km>h>1km. Pulse length 10 ms. Search for surface return AND hydrometeors. Binned samples at higher resolution around the surface bin each 3 seconds.
- Near surface mode, h<1km. Pulse length 2 ms. Search for surface structure and topography. Binned samples at highest resolution around the surface bin each second.
- Surface mode. After impact, search for depth of liquid. Pulse length 10 ms. Send one pulse, listen for 10 s. Binned data around the maximum return.

3.2 API-V Mode

API-V has one mode only and is operating at altitudes below 60 km. Sensor A transmits a sort pulse, 10 waves at 1 MHz, and starts a 4 MHz counter. Sensor B receives the pulse and stops the counter. Immediately afterwards the sequence is repeated in the reverse direction. The data from both counters is stored included in the telemetry. The measurement is repeated at 1 s interval.

3. THEORY

The following general formulas governing acoustic wave propagation and system performance form the basis for the design of a practical instrument for investigating the mentioned parameters on Titan. They are given without derivations which can be found in the basic literature [1,2].

4.1 Speed of sound, c

For a plane longitudinal wave propagating in an isotropic linear medium the speed of sound can be written generally as,

$$c = \sqrt{\frac{B}{\rho}} \tag{1}$$

where ρ is the density of the medium

and, for solid media,
B is the Young modulus (simplified equation)

while for gasses and liquids
$B = B_s(p,T)$ is the adiabatic bulk modulus
$B_s = \gamma B_t$
where
$\gamma = C_p/C_v$ is the ratio between the specific heat for constant pressure and the specific heat for constant volume, and
B_t is the isothermal bulk modulus.

For a liquid $\gamma \approx 1$ and for a gas usually $1.1 < \gamma < 1.4$

For an ideal gas we get:

$$c = \sqrt{\frac{\gamma R T}{M}} \tag{2}$$

where
$R = 8313$, is the molar gas constant (=k/u)
M is the molar weight and
T is the absolute temperature

The speed of sound for gasses and liquids does show some frequency dispersion due to molecular thermal relaxation. For the further discussion this dispersion will in the first instance be neglected, since the magnitude usually stays below 1%. Dispersion for mixtures of gasses though, can be higher.

4.2 Specific Acoustic Impedance

The acoustic impedance is of great importance for how the energy is coupled through an interface of two media with different impedances. This can be for example two subsurface layers or the transport of energy between a transducer and the surrounding medium or vice versa.

The specific acoustic impedance of a medium is defined as the ratio between the acoustic pressure, p, and the associated particle speed, u,

$$Z = \frac{p}{u} \tag{3}$$

Z is expressed in the unit Rayls, where
1 Rayl=1 Nsm^{-3}.
This quantity will for a lossy medium be complex, Z = r + jx, where the imaginary part relates to the absorptive losses in the medium. For a lossless medium we have,

$$Z = r = \rho c \tag{4}$$

By inserting (2) into (4) we get

$$Z = p\sqrt{\frac{\gamma M}{RT}} \tag{5}$$

The acoustic intensity, I [W/m^2], can be written as

$$I = pu = \frac{p^2}{Z} \tag{6}$$

4.3 Acoustic Attenuation

Absorption and scattering of energy both contribute to the attenuation of a propagating wave.

The acoustic intensity, *I*, of a plane wave propagating in an absorptive medium will decay exponentially,

$$I(x) = I(1)\, e^{-2\alpha x} \tag{7}$$

where
α is the absorption coefficient.
α can be divided into two components

$$\alpha = \alpha_c + \alpha_m$$

where
α_c is the classical absorption coefficient due to effects of the shear viscosity and thermal conductivity and
α_m is the absorption coefficient due to molecular thermal relaxation.

For gasses we have,

$$\alpha_c = \frac{\omega^2}{2\rho_0 c^3}\left[\frac{4}{3}\eta + (\gamma - 1)\frac{k}{C_p}\right] \tag{8}$$

where
η is the shear viscosity coefficient,
k is the thermal conductivity,
C_p is the specific heat capacity at constant pressure.

Note that α_c is proportional to the square of the frequency and inversely proportional to the density.

α_m is a function of frequency, sound velocity, the number of degrees of freedom and its respective relaxation times. For most gasses and liquids this expression becomes very complex. This is particularly true for mixtures of different compositions. α_m can be orders of magnitude larger than the classical absorption coefficient for some liquids and gasses.

Attenuation due to scattering in homogeneous media follow in principle the same rules as for electromagnetic waves. However, excitation of shear waves and surface waves at the interfaces and the fact that not all parameters are time independent makes it much more complicated. The theory of acoustic scattering is still not completely developed. Therefore scattering will not be treated further here. In a practical design though, it has to be carefully considered. This is done by careful calibration of the instrument in an environment as close as possible to where it will be used.

4.4 Reflection and Backscattering Coefficients

The power reflection coefficient, *R*, of a plane wave of intensity *I*, incident under angle θ_i on a medium of the (complex) specific impedance Z_2 from another medium with specific impedance Z_1 is,

$$R(\theta_i) = \frac{(r_2\cos\theta_i - r_1)^2 + x_2^2\cos^2\theta_i}{(r_2\cos\theta_i + r_1)^2 + x_2^2\cos^2\theta_i} \tag{9}$$

The backscatter coefficient, σ_0, is a dimensionless parameter characterising an object causing a reflection back in the opposite direction of the incident wave. It is a function of the specific impedances of the two media, the structure of the interface (D_{rms}; rms surface deviation, L; correlation length of D_{rms}), the wavelength and the incidence angle θ_i :

$$\sigma_0(\theta) = R(\theta) f(D_{rms}, L, \theta_i) \tag{10}$$

where *f* is a complicated function that usually has to be found experimentally.

For an isotropically scattering surface we have,

$$\sigma_0(0) = R(0)$$

4.5 Performance Equations

The performance of an acoustic SODAR and electromagnetic RADAR is calculated with the SODAR respective RADAR equations. The general form of these two equations is exactly the same. Traditionally the SODAR equation is operating on the logarithm of the numbers involved and consequently the product becomes a sum. We shall here however use the basic RADAR equation in its original form, as a product of terms. In the case where the target size is larger that the beam width it can be written as,

$$P_R = P_T\, \sigma_0\, \eta_T\, \eta_R \frac{A}{4\pi r^2} L \tag{11}$$

where
P_R and P_T are received respective transmitted power,
η_T is the transducer transmitting efficiency and
η_R is the transducer receiving efficiency,

A is the transducer area,
r is the target distance,
$L = e^{-4\alpha r}$ is the 2way loss due to atmospheric absorption
σ_0 is the acoustic backscatter coefficient cf. (10).

It is worth to note that this expression is independent of the frequency except from what is contained in α .

Hydrometeors, i.e. rain, snow hail etc., are certainly smaller than the beam of the transmitter but they make up clouds that normally are larger than the beam and therefore the same equation is valid, with a modification to the backscattering coefficient *σ0*. For hydrometeors we are concerned with volume scattering rather than surface scattering and therefore define the reflectivity factor, Z, which is dependent only on size of these scattering particles and the number of particles per unit volume. Examples of Z for a few hydrometeor conditions in the earth atmosphere are given in Table.

Table 1. Example of hydrometeors in the earth atmosphere and the respective reflectivity factors Z.

Hydrometeor condition	Precipitation rate [mm/h]	Z [mm6m-3]
Cloud		0.001 to 1
Fog		0.01 to 1
Drizzle	1	10
Light Rain	1	200
Heavy Rain	25	33000
Light Snow	1	1000
Heavy Snow	10	40000

The resolution in range (distance) that can be achieved from the (acoustic) radar, if the received signal passes a matched filter and is detected by envelope, can be expressed as,

$$\delta_R = \frac{c}{4B\sqrt{n\frac{S}{N}}} \qquad (12)$$

where
B is the bandwidth of the filter (= 1/pulse length),
n is the number of integrations,
S/N is the signal to noise ratio of the detected signal.

The Doppler shift of the received radar signal is

$$\Delta f = 2f\frac{v}{c}\cos\theta \qquad (13)$$

where
v is the relative velocity between the radar and the target, and
θ is the angle between the direction of the target and the velocity direction.

4.6 Transducer directivity

It can be shown that the acoustic field in front of a transducer of radius a, acting as a transmitter where all of the surface is excited with the same phase and amplitude (like a piston moving in a cylinder) can be expressed as,

$$H(\Omega) = \frac{2\,J_1(x)}{x} \qquad (14)$$

where
$J_1(x)$ is the first order Bessel function and
$x = \pi/\lambda\ d \sin \Omega$
where
Ω is the angle from the normal and
d is the diameter of the transducer.

Transmitting and receiving waves is a reciprocal process so the expression is identical for receiving signals. An important parameter of a transducer is the 3dB beam width. It can be found from (14) when $H(\Omega) = 1/\sqrt{2}$. A good approximation is $\Omega = \frac{1}{2}\lambda/d$.

In real transducers the edges of the surface are usually excited by lower amplitude than the centre. To account for this we get for the full 3dB beam width θ (= 2Ω),

$$\theta_{3dB} \approx 1.3\frac{\lambda}{d} \qquad (15)$$

The Directivity, D, of the transducer is defined as the ratio between the power density in the direction of maximum power and the power density for an isotropically radiating transducer at the same total output power. It can be written as,

$$D = \frac{4\pi A}{\lambda^2} \qquad (16)$$

4. NUMERICAL PARAMETERS ON TITAN

For a temperature of 95 K and a pressure of 1.5 bar we can calculate the following parameters as they should be at Titan.

5.1 Speed of Sound:

Table data taken from [3]:

Gasses :
N_2
0 ^{o}C, 1 bar 334 m/s
Scaling, (2) gives at Titan, 197 m/s

Traces of other gasses have only minor effects.

Liquids :

N_2	(74 K)	962 m/s
CH_4	(95 K)	1530 m/s
C_2H_6	(95 K)	1970 m/s

Traces of other liquids or solved gasses can have some effects.

Solids:
Solids normally range from 2000 m/s to 6000 m/s. Porous materials and sandy structures have to be treated with special theory.

5.2 Acoustic Impedance

The acoustic impedance is of great importance when designing a system where the coupling of acoustic energy between different media has to be considered. The coupling between a gas and a transducer is a typical example of this. Some examples of acoustic impedances are given in Table 2.

Table 2.

Gas	Nitrogen (Titan)	1062 rayls
Liquid	Most liquids	~10^6 rayls
Solid	Most solids	~10^7 rayls

Porous solids have a significant imaginary part (loss).

5.3 Acoustic attenuation

This is the most difficult parameter to estimate since the attenuation due to energy exchange between molecules, corresponding to the α_m term in (7), can be very complicated to calculate. This is particularly true for mixtures of gasses. Even a small fraction of one gas in another can drastically change the attenuation orders of magnitudes. Water vapour in air is a typical example of this. Further it is notable that the classical term α_c is proportional to f^2.

Some examples of measured valves of α/f^2 are shown in Table 3 [3].

From (8) we can see that α_c is proportional to $1/\rho$

ρ in turn is proportional to p/T. Hence the valves of α_c for gasses can be scaled to 95 K, 1.5 bar with the factor

$$\frac{\alpha_c(1.5bar,95K)}{\alpha_c(1bar,293K)} = \frac{95}{293}\frac{1.0}{1.5} = 0.22 \qquad (17)$$

From (17) and Table 1 we can then calculate α_c for Nitrogen at 95 K, 1.5 bar and 15 kHz. We get,

$$\alpha_c = 0.81 \cdot 10^{-3}\ m^{-1}; \quad \text{-->} \quad 0.7\ dB/100\ m.$$

We see that for a practical system the limitation will not be in the classical term of the absorption coefficient α. It is likely that the term α_m will be the dominating part of the total absorption. Since this term is more difficult to calculate, real low temperature measurements are required to reliably estimate the actual absorption.
For liquids, α is less sensitive to pressure and temperature, and is anyhow typically 10^{-14} $Hz^{-2}m^{-1}$ which is a factor 1000 less than for gasses. In a liquid a short-range system like the API should therefore not be limited by the absorption coefficient.

Table 3.

α/f^2	Gas	Liquid
	20 °C, 1 bar	74-85 K, 1 bar
	10^{-11} $Hz^{-2}m^{-1}$	10^{-15} $Hz^{-2}m^{-1}$
Argon	1.87	10.1
Helium	0.54	--
Oxygen	1.92	8.6
Nitrogen	1.64	10.6

5. CALIBRATION AND PERFORMANCE

Since some of the acoustic parameters are difficult to compute and since the environment where the instrument shall operate is not fully known, calibration of the API is of the highest importance. API-V has been calibrated in the most common gasses and liquids at representative temperatures in the Titan simulation chamber at University of Kent, Canterbury UK. The global results are shown in Fig. 4 and Fig. 5.

To estimate the maximum altitude for operation of API-V, the sensor pair was operated at reduced pressure in a vacuum chamber at room temperature. It was found that the sensor operates well down to at least 40 mbar, if the full ten waves in the pulse are accounted for in the receiver. This is shown in Fig. 6. From (5) we can compute that this corresponds to about 60 km altitude on Titan.

For a signal strong enough to be detected, the absolute accuracy of the sound speed is determined by the interval of the counter (250 ns) measuring the time of the pulse transiting the path between the two transducers. This results in an accuracy of about 0.03% for the sound speed measurement. If we assume an accuracy of 0.1 K for the temperature measurement error analysis of (5) gives a total error in the estimate of the mean molecular weight to 0.1 %. This is sufficient to make useful contributions to the estimates of the mixing ratio along the descent trajectory path.

A proper full-scale calibration at Titan conditions for the API-S is not possible since it would require a Titan simulation chamber of impossible dimensions. The API-S sensor has therefore been characterised at Titan temperatures and together with open-air tests in a normal laboratory environment performance at Titan has been computed. These results are summarised in Fig. 7. From this figure and from Table 1, we find that if we assume the same condition as on earth, any condition more intense than drizzle should be detectable by API-S assuming a detectable threshold S/N of 1.

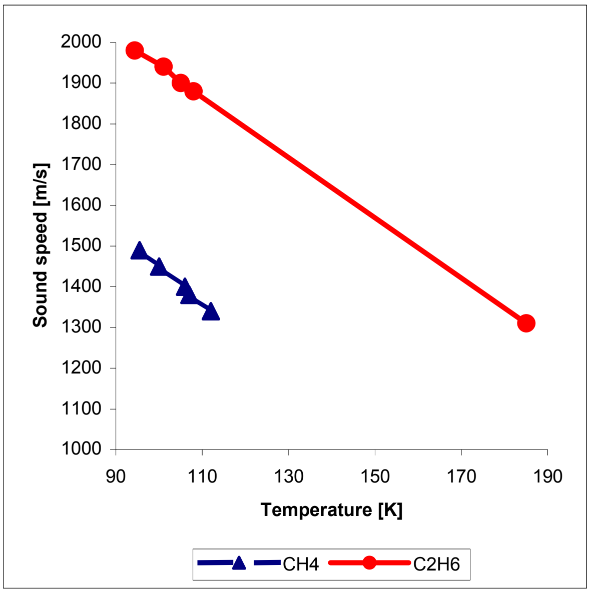

Fig. 4. Sound Speed for liquid Methane and liquid Ethane from sensor calibration measurements at UKC.

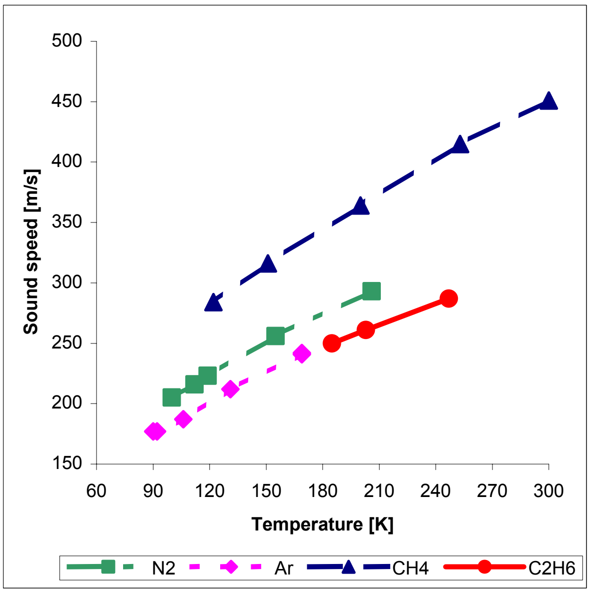

Fig. 5. Sound Speed for gaseous Nitrogen, Argon, Methane and Ethane from sensor calibration measurements at UKC.

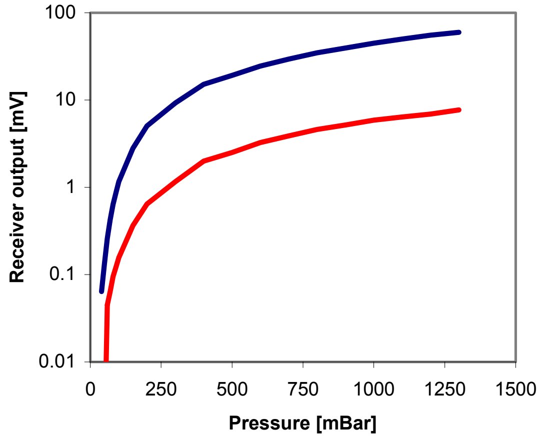

Fig. 6. API-V sensitivity to ambient pressure at room temperature. The electronics detection limit is ~ 5μV.

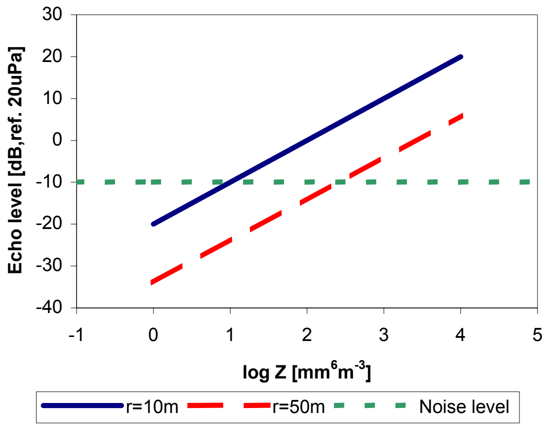

Fig. 7. Performance chart for the API-S. Examples of the reflectivity factor, Z, can be found in Table 1.

6. CONCLUSIONS

The Acoustic Properties Investigation on Titan will provide information on the composition of the Titan atmosphere via measurements of the mean molecular weight as a function of height above the surface. The accuracy of the mean molecular weight is about 0.1%.
If any hydrometeors will exist along the descent trajectory these will be detected down to the intensity corresponding to a light rain on earth. Depending on the amount of scatterers and inhomogenities in a possible liquid layer on the surface, the thickness (depth) of this layer may be detectable down to 1000m.

7. ACKNOWLEDGEMENS

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