HASI TEM Data processing and Calibration Report

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HASI TEM Calibration Report

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1. Acronyms

C1, C2	TEM 1 (TEM 2) Coarse sensor TM packets (TM formats #98 and #102)
F1, F2	TEM 1 (TEM 2) Fine sensor TM packets (TM formats #96 and #100)
HASI	HUYGENS Atmospheric Structure Instrument
TEM	TEMperature sensors (STUB s/s)
STUB	STUB subsystem
RTD	Resistance Temperature Detector

2. Scope of the Document

Scope of the document is to report on the procedure and results of the calibration of the HASI Temperature Sensors TEM and to present guidelines for data processing and the reconstruction of the Temperature value.

3. Applicable and Reference Documents

[AD1] Cassini Mission Huygens Probe Huygens Atmospheric Structure Instrument – STUB-FM Acceptance data Package Document HASI-ADP-FM-UPD-016 (II/172.B.6)

[AD2] HASI Experiment Flight User Manual Document HASI-MA-OG-002 Issue 3, 1 December 1998 (II/196.B.6)

[AD3] HAS DPU Software User Requirements Document HASI-SP-OG-004, Issue 7, 7 Sep 1995 (II/179.B.1)

[AD4] Rosemount Aerospace Inc. – Report of Calibration 05-Jun-95 values included as annex in [AD1]

[AD5] ITS90 Preston-Thomas, **The International Scale of 1990 (ITS-90)** *Metrologia* **27**, 3-10, 1990.

[AD6] HASI DPU subsystem Proto- Flight Model Summary Report HASI-RP-OG-047 Issue 1 04/06/96 (II/188.C.4)

[RD1] Ruffino, G., A. Castelli, P. Coppa, C. Cornaro, S. Foglietta, M. Fulchignoni, F. Gori and P. Salvini, **The temperature sensor on the Huygens probe for the Cassini mission: design, manufacture, calibration and tests of the laboratory prototype,** *Planet. Space Sci.*, Vol. **44**, Issue 10,1149-1162, 1996.

[RD2] Angrilli, F., Bianchini, G., Debei, S., Fanti, G., Ferri, F., Fulchignoni, M. and Saggin, B.1996**. First results of performance test of temperature sensors of HASI instrument on Cassini/Huygens mission**. In Proceedings of SPIE-International Society for Optical Engineering, 5-6/08/1996,Denver, Colorado, U.S. 2803,75-83, 1996.

[RD3] Saggin, B. F. Angrilli, G. Bianchini, S. Debei, G. Fanti, F. Ferri, **Analysis of dynamic performances of HASI temperature sensor during the entry in the Titan atmosphere** Planet. Space Sci, Vol. 46, No.9/10, 1325-1332, 1998.

[RD4] SAGGINETAL2001
Saggin, B, S. Debei, M. Zaccariotto, **Dynamic error correction of a thermometer for atmospheric measurements**, *Measurement* **30**, 223–230, 2001.

TEM sensor description

HASI temperature sensors are two redundant dual element platinum resistance thermometers (TEM) mounted on the STUB in order to be appropriatelly located and oriented with respect to the gas flow during the measurements.
Each TEM has a primary sensor (fine, F) directly exposed to the air flow and a secondary sensor (coarse, C) which is annealed in glass of the supporting frame and is used as spare unit in case of damage on the primary sensor.
TEM's main sensing element (FINE) is a fine-wire platinum resistance thermometer, 0.1 mm in diameter. It is wound around a platinum (Pt) support frame ~6 cm long and ~3 cm wide, configured as a double coil of 19 turns directly exposed to the atmosphere. The wire is approximately 1.2 m long, with 16 Ohm resistance at 0 deg C. It is insulated from the frame by covering the outer posts with a thin layer of a lead glass, while a second layer of the same glass holds the windings in their proper position. The COARSE secondary sensing element, which will guarantee temperature measurements even if FINE sensor is damaged, is attached to the top (windward) of the support frame. It is a 40 cm-long insulated wire platinum resistance thermometer, 0.05 mm in diameter, with a ~19 Ohm resistance at 0 deg C. In order to include the TEM units in the global Huygens Faraday cage, the sensors are coated with 25 um of paralyne and 0.1 um of gold.

4 sensors:
- TEM1 fine (F1)
- TEM1 coarse (C1)
- TEM2 fine (F2)
- TEM2 coarse (C2)

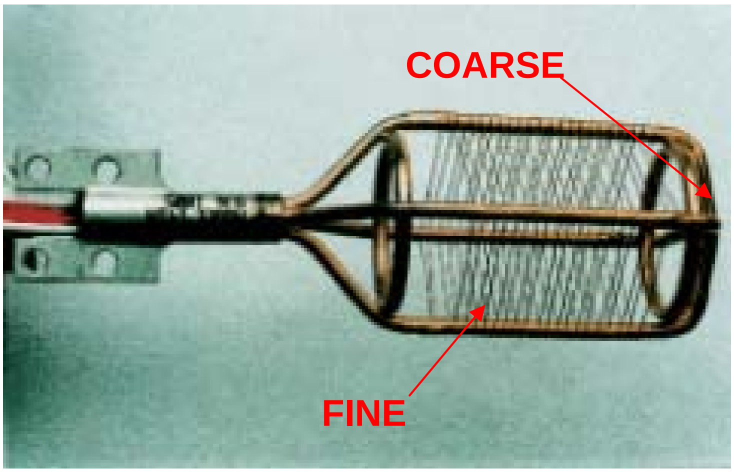

Figure 1 TEM sensor

3.1. TEM location and accommodation

The two TEM units mounted on the STUB are located outside Huygens' probe boundary layer, in a region where local flow velocity around Huygens is high, in order to avoid thermal contamination and promote very fast response.
It is possible to see in Figure 1 the position of the TEM1 sensor; the "unlucky" position near the SEPS (SEParation Subsytem) needs an accurate analysis and interpretation of temperature

measurements conducted during Titan mission: a comparative analysis with TEM2 data will clarify the influence of the SEPS on the performance of the sensor.

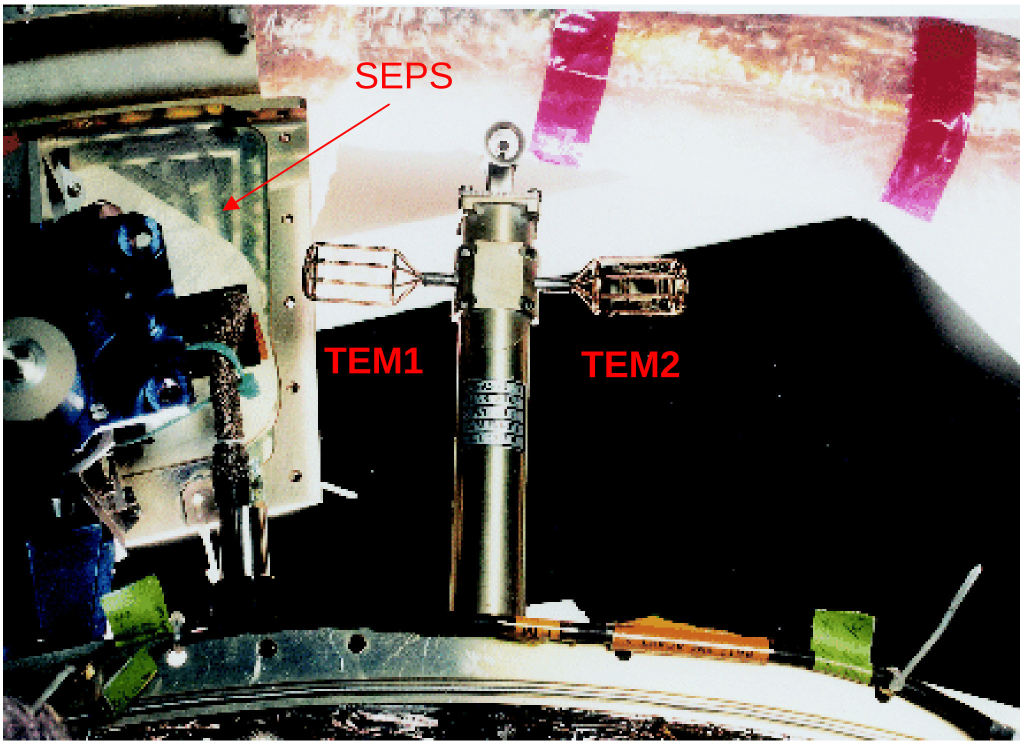

Figure 2 HASI STUB carrying the two HASI TEM units

3.2. Measurements principle and data sampling

Temperature measurement is performed by monitoring the resistance of TEM sensors; the resistance of each TEM sensor is measured by a four wire configuration (ref to [AD2]). For a complete discussion of the measurement principle and how the temperature value is reconstructed from data refer to §10.

3.3. Operational modes

HASI starts to sample TEM sensor at the beginning of the descent phase, starting from T0+10s (=Tdata) when the sensors are still under the front shield (front shield jettisoning at T0+32.5s) in order to get data during the transitional phase helping to connect entry and descent profiles.
All 4 TEM sensors are sampled every 5 s. The measurement sequence is the following: F1, C1, F2, C2, F1, C1...
Sampling rate:

- 1 Temperature point every 1.25s (0.8 Hz)
- but same sensor sampled every 5s (0.2Hz)

In IMPACT STATE only F1 and F2 are sampled

- 1 Temperature point every 1.25s (0.8 Hz)
- but same sensor sampled every 2.5s (0.4Hz)

Temperature measurements can be performed in HIGH and LOW resolution range (60-110K for HIGH and 100-330K for LOW resolution) by switching HIGH and LOW gain channel. The range selection is performed by HASI S/W calculating the rough resistor value and comparing against a setable threshold.

Range (60-110K)		**Range (90-330K)**	
Resolution	<0.02K	Resolution	<0.07K
FINE absolute accuracy	<0.5K	FINE absolute accuracy	<2K
COARSE absolute accuracy	<0.8K	COARSE absolute accuracy	<2K

Table 1 TEM characteristics and performance (temperature profile with altitude)

3.4. Telemetry output

The measured values used to reconstruct the thermometer resistance (and temperature from postprocessing) are timestamped (mission time=native time) and stored in TM packet by sensor type:

Sensor	TM data format
TEM1FINE	#96
TEM1COARSE	#98
TEM2FINE	#100
TEM2COARSE	#102

Time relevant to each data value is derived from the packet time stamp and the TEM sampling rate and scheme.

4. Pre-flight Calibration

During development of TEM static and dynamic calibration campaigns were conducted for different model type of sensors. Below are presented only the calibration campaigns for the 141M model that was selected for the HASI TEM Flight Model (FM).

4.1. Static Calibration

Static calibration was performed by Rosemount Inc. in 1995 using the standard ITS90 procedures. Calibration points selected are as in table

Temperature [K]	**material**
77	Liquid Nitrogen (LN2)
123	R12 & R13 Freon CFCs
203	Trichlor Ethylene
273	Trichlor Ethylene

Table 2 Points used for Static Calibration

Temperatures measured by sensor are determined in terms of the ratio of the resistance $R(T_{90})$ at a temperature T_{90} and the resistance R(273.16 K) at the triple point of water. This ratio, $W(T_{90})$ is defined as:

$$W(T_{90}) = R(T_{90}) / R(273.16K)$$ **Eq. 1**

In the calibration range selected, T_{90} is defined by means of a platinum resistance thermometer calibrated at the above specified sets of defining fixed points, and using specified reference and deviation functions for interpolation at intervening temperatures.
The deviation function is:

$$W(T_{90}) - W_r(T_{90}) = a[W(T_{90}) - 1] + b[W(T_{90}) - 1]^2 + c_1 \ln^2(W(T_{90}))$$ **Eq. 2**

with values for the coefficients a, b and c_1 being obtained from measurements at the defining points.
Calibration data obtained by Rosemount (as in HASI-ADP-FM-UPD-016 [AD1]) are as in Table 3 & Table 4:

coefficient	Primary Sensor	Secondary Sensor
R_{TP}	15.0254	15.0820
a	1.8315809E-04	-2.3039900E-03
b	5.5440289E-04	-2.0659308E-03
c1	1.9100452E-05	1.6952969E-04

Table 3 TEM 1 (Sensor SN:1010 fine, coarse)

coefficient	Primary Sensor	Secondary Sensor
R_{TP}	15.0751	15.0447
a	1.3919570E-03	-4.8133285E-04
b	3.4337150E-03	2.3606054E-03
c1	-3.0606478E-04	-3.3814668E-04

Table 4 TEM 2 (Sensor SN:1011 fine, coarse)

Where R_{TP} is the value of the RTD at the triple point of water.

4.2. Dynamic Calibration

The dynamic calibration of TEM is aimed at the determination of the time response of the sensors. It was performed in early 1995 by Rosemount Aerospace at Burnsville wind tunnel with a special setup developed specifically for HASI TEM sensor (Fig. 1). Different dynamic conditions covering the expected operational range for TEM have been investigated in few test run. Test run specification and results are reported in APPENDIX A
Figure 4 reports the response time of the two different sensors (primary & secondary).as a function of flow rate.

As it can be seen the primary sensor has a response time that is 10 times the one of the secondary sensor. Secondary sensor has, in first approximation, same response time as the supporting structure since it's embedded in the glass on the metallic cage.

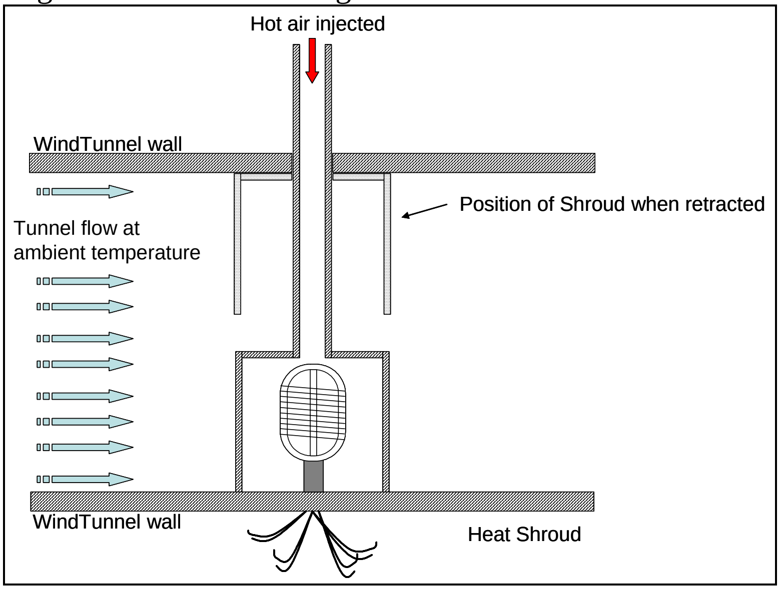

Figure 3 Wind tunnel response time scheme

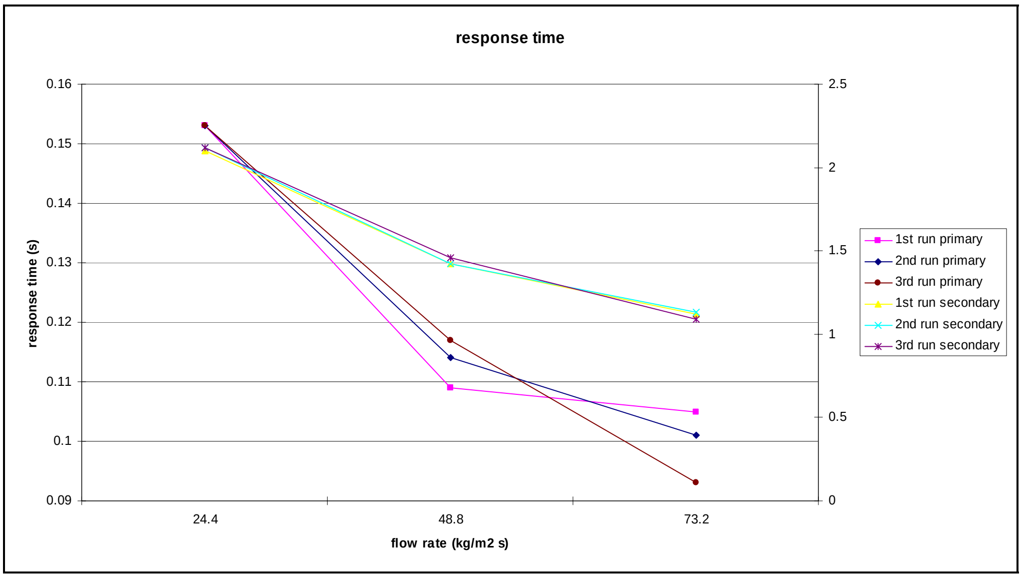

Figure 4 Response time as calculated from wind tunnel tests

4.3. Dynamic performance of TEM sensor

A numerical model of HASI TEM combined with the experimental results of the qualification and acceptance tests (ref [AD1]) for the dynamic characterization of the thermometer showed that the behaviour is quite different from that of a 1st order system (Angrilli et al., 1996, [RD2]). Modelling the sensor only by means of the time constant of the sensing wire does not account for the effect of

the mechanical structures thermal inertia; in fact a more accurate dynamic characterization of the sensor requires three parameters that depend on the thermo-fluid environment.
An accurate model for the HASI TEM sensor (Saggin et al.,1998, [RD3]) can be described by:

$$\tau_1 \tau_2 \frac{d^2 T_W}{dt^2} + (\tau_1 + \tau_2)\frac{dT_W}{dt} + T_W = \tau_3 \frac{dT_a}{dt} + T_a \qquad \textbf{Eq. 3}$$

where T_w and T_a are respectively the temperature of the sensing wire and of the atmospheric fluid.
The three parameters τ_1, τ_2 and τ_3 required to characterize the sensor dynamic behaviour are respectively: τ_1 is the response time that the sensing wire would exhibit exchanging heat with the ambient only by convection, τ_2 depends mostly on the thermal coupling between the wire and the structure and τ_3 is the response time of the supporting structure.
The time constants τ_i depend mainly on the convective factors between the various parts of the sensor and the fluid, the conductive links between the sensing wire and the structure and the thermal capacities. The last two time constants will exhibit only slight changes during the descent of the probe in Titan atmosphere, while the 1st will change dramatically from the beginning to the end of the descent. Therefore the knowledge of the dynamic behaviour requires the knowledge of all the three parameters τ_i.

Altitude	τ_1	τ_2	τ_3
0	0.14	2.03	1.67
14	0.18	2.75	2.22
30	0.23	3.95	3.13
58	0.36	6.71	5.02
102	0.43	8.60	6.17
150	0.53	7.74	4.81

Table 5. Dynamic parameters of the sensor at various altitudes (Saggin et al.,1998, [RD3])

The parameters in Table 5 allow determining the sinusoidal transfer function at various altitudes; the module of the sinusoidal transfer function of the thermometer is plotted in **Figure 5**. The frequency response is important because on the base of the characteristics of the acquisition system, it allows to decide whether an “a posteriori” correction of the readings is required or not. The sampling frequency adopted for the thermometer is of 0.4 Hz during most of the descent and 0.8 Hz only during the last kilometre. The sampling theorem states that it is useless (even dangerous) having a bandwidth of the system higher than half of the sampling frequency; therefore the optimal thermometer should have a bandwidth of 0.2 Hz (0.4 during the last km). (Saggin et al.,1998, [RD3])

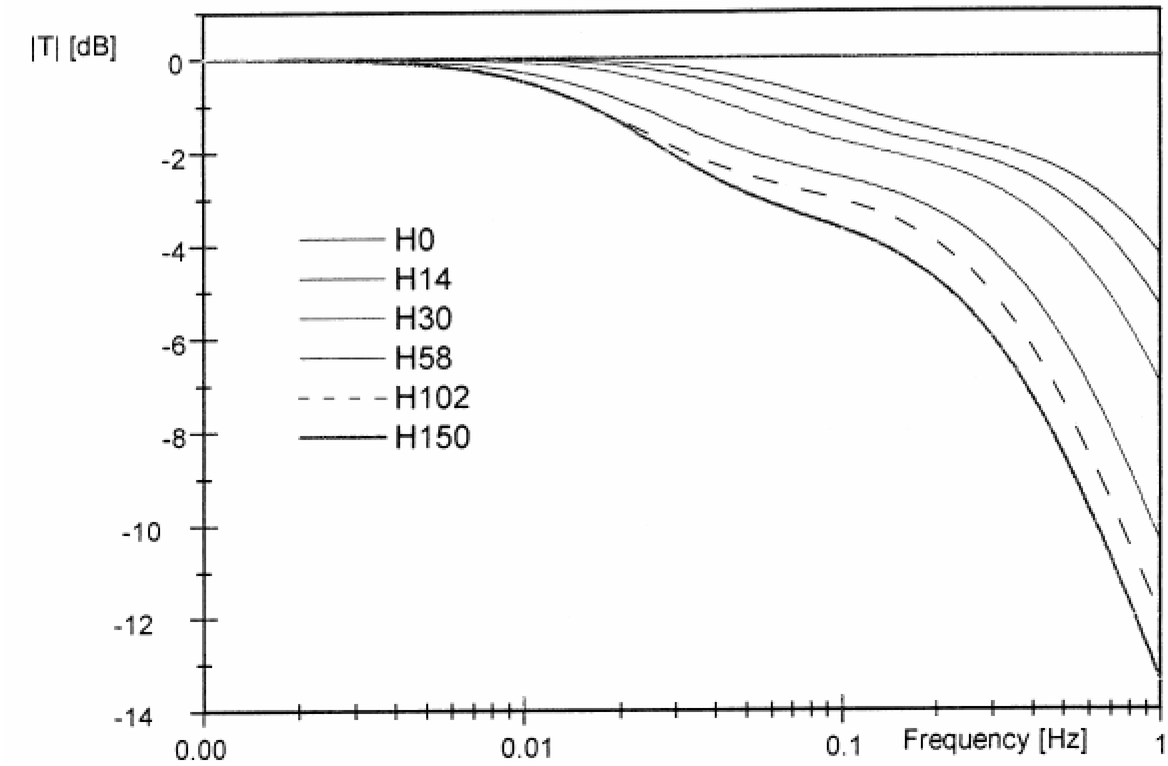

Figure 5 Module of the TEM sinusoidal transfer function at various altitudes during the descent

The correction of the dynamic behaviour of the thermometer will be performed as described in [RD4].

5. Dynamic corrections on temperature measurements

Temperature measurements are relevant to total values and have to be corrected taking into account the dynamic conditions:

$$T_{stat} = \frac{T_{meas}}{\left(1 + r\frac{\gamma - 1}{2}Ma^2\right)} \qquad \textbf{Eq. 4}$$

Where T_{meas} are the values really measured by the sensors, $\gamma = c_p/c_v$ is the ratio of the specific heat constants, *Ma* is the Mach number and *r* is the recovery factor, accomplished by experimental calibration.

The dynamic correction of the measured temperature profiles will be carried knowing the Mach number.

6. In-flight Calibration

During the cruise phase HASI experiment and the Huygens probe has been switched on regularly for performing in-flight CheckOut (CO). These COs have been performed approximately every 6 months since launch, to test the probe and its subsystems during simulated entry, descent and surface proximity phases and also to upload SW patches.

TEM have been subjected to a test sequence during each CO (see **Figure 6**), monitoring the temperature conditions inside the front shield. In space conditions (zero-g and vacuum) no convection is present and TEM sensors exchange heat by mainly radiation and conduction.

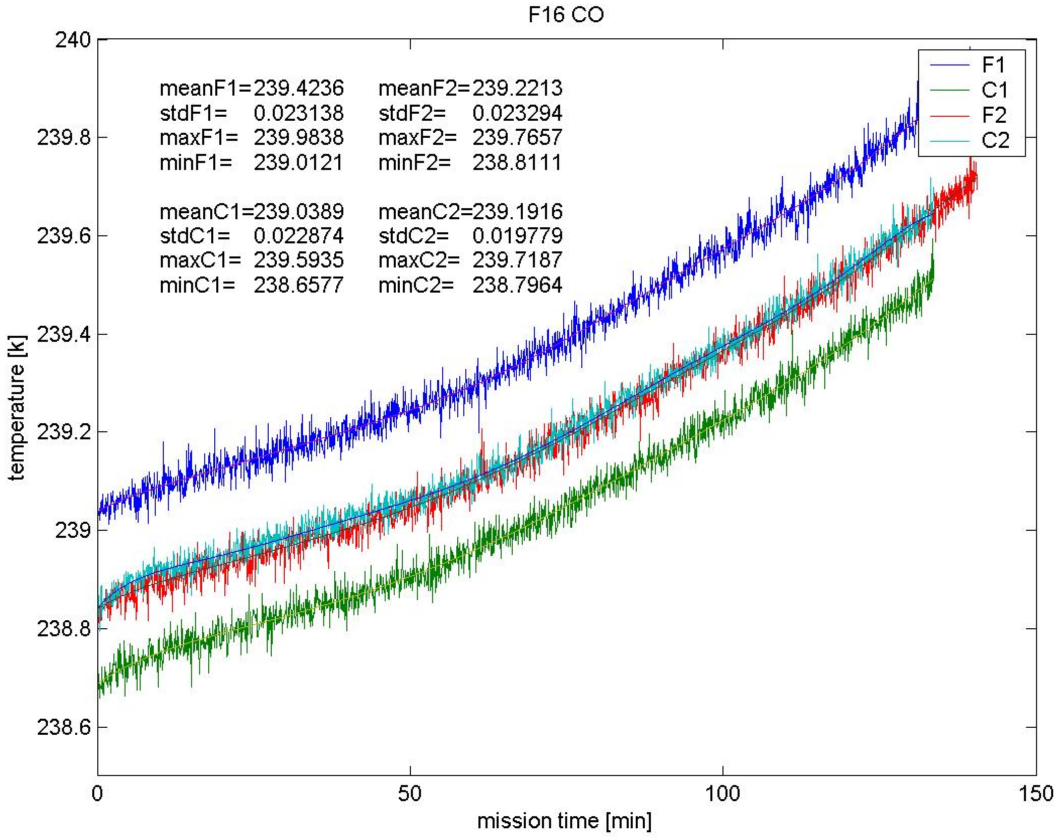

Figure 6 TEM measured temperatures during in flight CheckOut #16

During the COs temperature raises approximately around 1K depending of the type of the CO itself and on the duration of the test.
It is important to notice that the TEM1 sensor measurement is affected by the heat radiated by the SEPS system and the difference of the temperature measured is due to the "unlucky" position of the sensor itself (see Figure 2); in **Figure 7** it's possible to observe that while the two sensor TEM2FINE and TEM2COARSE have the same temperature the difference between the two sensors of the TEM1 is significant.

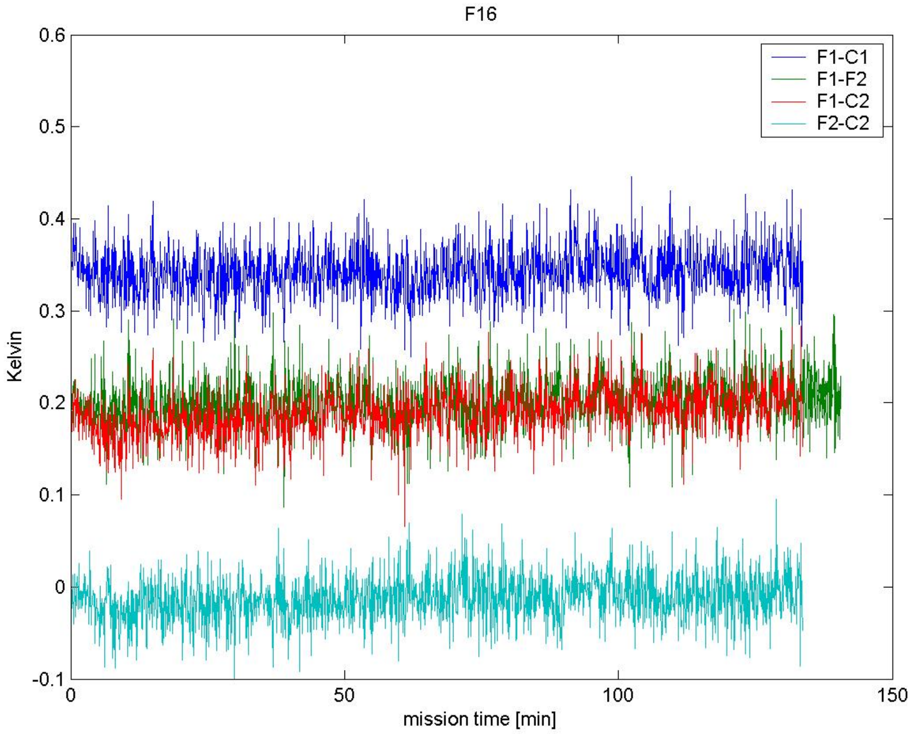

Figure 7 Difference of the TEM measurements during in flight CheckOut #16

It is not possible to perform an in flight calibration since there is not a more accurate reference sensor on the probe that can be used. The only purpose is to check the status of the sensor and eventually monitor any drift and/or ageing effect.

7. TEM Total Error Budget Estimate

In Table 6 is presented a summary of all the uncertainties that are significant for the Temperature reconstruction process.

UNCERTAINTY ITEM DESCRIPTION	TEMPERATURE RANGE 60K-110K	TEMPERATURE RANGE 110K-330K
SENSOR STATIC ACCURACY	±0.01 K	±0.01 K
ORIGINAL CALIBRATION UNCERTAINTY	±0.0025 K	±0.0025 K
DPU CONTRIBUTION		
SAMPLING ERROR (extended range)	±0.01 K	±0.03 K
SIGNAL NOISE RMS	±0.04 K	±0.05 K
SHORT TERM STABILITY (conversion accuracy)	±0.05 K	±0.06 K
LONG TERM STABILITY (mainly due to standard reference resistor drift: 0.1% in 17 year)	±0.07 K	±0.12 K
DYNAMIC EFFECTS	**Altitude 30 km**	**Altitude 50 km**
SENSOR TIME CONSTANT	0.15±0.02 s	0.5±0.1 s
FRAME TIME CONSTANT	2.0±0.5 s	7.7±1.3 s
GLOBAL UNCERTAINTY With TEM outside the probe boundary layer		
Repeatability	<±0.05 K	<±0.1 K
Accuracy	<±0.25 K	<±1 K

Table 6 Uncertainties for HASI TEM sensor

8. TEM data processing: Engineering Value reconstruction

Data Formats: #96 – F1
#98 – C1
#100 – F2
#102 – C2

Data Field Contents:

- 18 TEM subfields of 48 bit (3 words) each
- 2 OFFSET subfields of 16 bit (1 word) each

Data Field Layout:

Word 0	T1a	T0a
Word 1	T3a	T2a
Word 2	T5a	T4a
Word 3	…	…
Word 4	…	…

Word 54	OVFMEAN
Word 55	OVRMEAN

8.1. Extraction

First step is the extraction of the subfileds from the TEM packet.

RawVal_VF bit 8-23
RawVal_OVF bit 1-7
RawVal_Gain bit 0
RawVal_VR bit 32-47
RawVal_OVR bit 25-31

RawVal_OVFMEAN bit 0-15
RawVal_OVRMEAN bit 0-15

8.2. Normalisation

Second is the normalisation of the data since data are collected as sum of 8 or 4 samples

Val_VF = RawVal_VF/8
Val_OVF = RawVal_OVF/4
Val_Gain = RawVal_Gain (single values)
Val_VR = RawVal_VR/8
Val_OVR = RawVal_OVR/4
Val_OVFMEAN = RawVal_OVFMEAN/8
Val_OVRMEAN = RawVal_OVRMEAN/8

8.3. Engineering conversion

Final step is to convert the data in engineering values:

VF = Val_VF*10*2^{-12}
OVF = Val_OVF*10*2^{-12}
Gain = Val_Gain (0=LOW; 1=HIGH)
VR = Val_VR*10*2^{-12}
OVR = Val_OVR*10*2^{-12}
OVFMEAN = Val_OVFMEAN*10*2^{-12}
OVRMEAN = Val_OVRMEAN*10*2^{-12}

9. TEM data processing: Scientific Value reconstruction

For the Temperature measurement the resistance value of the sensor head is measured via the calculation of the ratio between the tension measured on the sensor head (V_F) and the tension on a reference resistor (V_R). The measurement principle consists in injecting a constant pulsed current (25 mA for 50ms) through the sensor head and the reference resistor and measuring the two voltages (see [AD2] HASI-MA-OG-002 §3.8.3.3):

$$R_{TEM} = K\left[\left(\frac{V_F - V_{F\_OFF}}{V_R - V_{R\_OFF}}\right) + 1\right] \quad \textbf{Eq. 5}$$

K = REFERENCE resistance – RBR 56 type
V_F = Sensor head measured voltage
V_R = REFERENCE measured voltage
V_{F_OFF} = post processed Sensor head offset voltage
V_{R_OFF} = post processed REFERENCE offset voltage

K depends on the resolution range selected during measurement (as function of the reference resistance included in the circuit):

REFERENCE RESISTANCE for the FM model	
HIGH resolution range (60-110K)	1.5077
LOW resolution range (100-330K)	4.0276

Table 7 Reference resistance for the FM model

V_{F_OFF} and V_{R_OFF} are calculated as follows:

V_{F_OFF} =[(RawVal_OVF <<1) | (RawVal_OVFMEAN & 0xff00)]*adu
V_{R_OFF} =[(RawVal_OVR <<1) | (RawVal_OVRMEAN & 0xff00)]*adu

With adu = [10 / (4096 * 8)] and “<<”, “|”and “&” are the C language bit operators “left shift”, “Or” and “And” respectively.

Then the ITS90 procedure [AD3] is used for calculating the Temperature value.
First the value $W = R_{TEM} / R_{tp}$ is calculated.
Then the reference function is calculated inverting **Eq. 6**:

$$W_r = W - a[W - 1] - b[W - 1]^2 - c_1 \ln^2(W) \qquad \textbf{Eq. 6}$$

and the temperature is:

$$T / 273.16K = B_0 + \sum_{i=1}^{15} B_i \left[\frac{W_r^{1/6} - 0.65}{0.35} \right]^i \qquad \textbf{Eq. 7}$$

where B_i are tabled coefficients (see APPENDIX B- Table 9).

10. APPENDICES

10.1. APPENDIX A

FLOW RATE (kg/sq meter second)	Run Number	Response Time Primary element (seconds)	Response Time Secondary element (seconds)
24.4	1	0.153	2.10
	2	0.153	2.12
	3	0.153	2.12
48.8	1	0.109	1.42
	2	0.114	1.42
	3	0.117	1.46
73.2	1	0.105	1.12
	2	0.101	1.13
	3	0.093	1.09

Table 8

10.2. APPENDIX B: Calibration data

TEM calibration coefficients

Resistance value

$$R_{TEM} = K\left[\left(\frac{V_F - V_{F\_OFF}}{V_R - V_{R\_OFF}}\right) + 1\right] \quad \textbf{Eq. 5}$$

RTEM=K*(((VF-VF_OFF)/(VR-VR_OFF)) +1)   Eq. 5 *in ascii format*
where VF, VF_OFF, VR, VR_OFF are derived from engineering data

K values to be used in Eq. 3 (to compute R_{TEM} value starting from measured tensions):

Reference resistance for the FM model in ASCII format
HIGH resolution range (60-110K)   1.5077
LOW resolution range (100-330K)   4.0276

Reference resistance for the FS model in ASCII format
HIGH resolution range (60-110K)   1.5075
LOW resolution range (100-330K)   4.0312

Temperature value: Transfer function
Reference function:

$$W = R_{TEM} / R_{tp}$$

W=RTEM/RTP

$$W_r = W - a[W-1] - b[W-1]^2 - c_1 \ln^2(W) \qquad \textbf{Eq. 6}$$

WR=W-a(W-1)-b(W-1)^2-c1(ln(W))^2

and the temperature is:

$$T / 273.16K = B_0 + \sum_{i=1}^{15} B_i \left[\frac{W_r^{1/6} - 0.65}{0.35} \right]^i \qquad \textbf{Eq. 7}$$

T/273.16K=B0+SUM(Bi[(Wr^(1/6)-0.65)/0.35]^i, i=1…15)

TEM calibration coefficients:

[Sensor, RTP, a, b, c1]

TEM1F, 15.0254, 1.8315809E-04, 5.5440289E-04, 1.9100452E-05

TEM1C, 15.0820, 1.8315809E-04, 5.5440289E-04, 1.6952969E-04

TEM2F, 15.0751, 1.8315809E-04, 5.5440289E-04, 3.0606478E-04

TEM2C, 15.0447, 1.8315809E-04, 5.5440289E-04, -3.3814668E-04

As from Table3 & 4

TEM 1 (Sensor SN:1010 fine F, coarse C)

TEM 2 (Sensor SN:1011 fine F, coarse C)

ITS90 B coefficient

[B0, B1, B2, B3, B4, B5, B6, B7, B8, B9, B10, B11, B12, B13, B14, B15]

[0.183 324 722, -0.056 470 670, 0.240 975 303, 0.076 201 285, 0.209 108 771, 0.123 893 204, 0.190 439 972, -0.029 201 193, 0.142 648 498, -0.091 173 542, 0.077 993 465, 0.001 317 696, 0.012 475 611, 0.026 025 526, -0.032 267 127,-0.075 291 522]

or

B0	0.183 324 722	B9	-0.056 470 670
B1	0.240 975 303	B10	0.076 201 285
B2	0.209 108 771	B11	0.123 893 204
B3	0.190 439 972	B12	-0.029 201 193
B4	0.142 648 498	B13	-0.091 173 542

B5	0.077 993 465	B14	0.001 317 696
B6	0.012 475 611	B15	0.026 025 526
B7	-0.032 267 127		
B8	-0.075 291 522		

Table 9