The University of Texas at Austin
Aerospace Engineering and Engineering Mechanics
Cockrell School of Engineering

ASE 375 Electromechanical Systems
Section 14115

Monday: 3:00 - 6:00 pm

Report 2:
Temperature Sensor Measurements

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Contents

1 Introduction

This experiment consisted of measuring temperature with three different sensors: a Thermocouple, Thermistor, and an Integrated Circuit Temperature sensor. Data collection was made possible through a Data Acquisition (DAQ) system used to process the different temperature measurements in LabVIEW, a graphical interface that modeled the temperature sensors' measurements in real-time.

The purpose of this experiment was to learn how to simulate our data through LabVIEW along with observing and understanding the behaviour of the three temperature sensors in different environments: (1) at room temperature, (2) in water near freezing conditions, and (3) in water closer to boiling conditions.

2 Equipment

The equipment used in this experiment include the following:

K-type Thermocouple: Temperature sensor with two different metals joined together at one end. A K-type thermocouple uses Chromel-Alumel metals. It will be connected to the DAQ via the NI 9211 thermocouple input module.

SA1-TH Series Thermistor: Temperature sensor that measures electrical resistance as a response to a change in temperature. It is connected to the NI 9215 via breadboard in its own circuit with 1kΩ resistor.

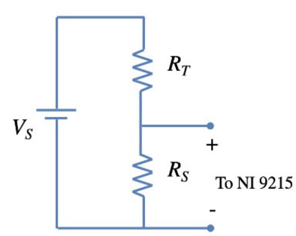

Figure 1: Thermistor Circuit

TMP36 Temperature Sensor: Analog low voltage sensor. It is connected to the NI 9215 via the breadboard.

Breadboard: a reusable solderless prototyping board used for building electronic circuits. Components are inserted into interconnected rows and columns of holes, allowing for easy and temporary assembly of circuits for testing and experimentation.

Circuit Components: various length male-to-male jumper wires, 1kΩ resistor, 5V power supply.

DAQ: Data Aquisition system that digitizes analog information into "bins" for a computer. The specific DAQ had two units, the NI 9215 and NI 9211. Specific Datasheets for each are included in the appendices.

Thermometer: Regular mercury thermometer, using change in volume as a response to a change in temperature. Used to measure true temperature with 0.5 degrees least count.

Water: Access to water at two temperatures, near boiling, and ice cold.

3 Procedure

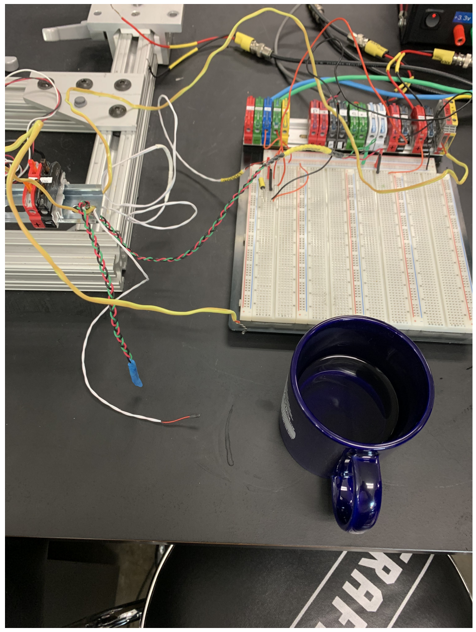

Figure 2: Temperature Sensors, Water mug, and Breadboard circuit

The DAQ, with the NI 9211 and NI 9215 modules already installed, was connected to an external 5V power supply as well as to the computer. The LabVIEW software is used to digitize the data from the temperature sensors. To do this, the following block diagram was created.

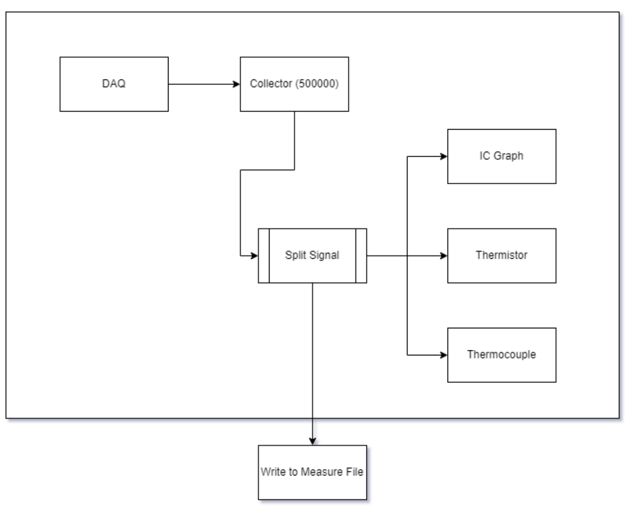

Figure 3: Process Diagram

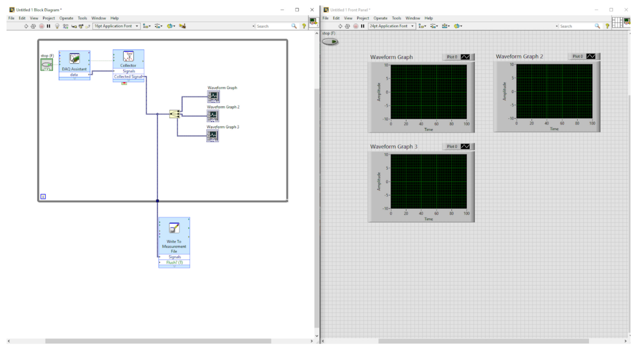

Figure 4: Process Diagram screenshot

The DAQ block had signals for each sensor, measuring at a 1000hz frequency. The collector is initially given a size of 500,000 samples. Each sensor from the DAQ was given its own graph using a split signal, and a "write to measure file" block was placed to save our data to an Excel file.

Now that our digital sensing was set up, we had to create the physical circuits. The thermocouple was connected directly into the NI 9211 module. The NI 9215 and power supply were connected to a breadboard. The Thermistor was connected to a 1kΩ resistor in a voltage divider configuration. The TMP36 was connected to the 5V power supply and the NI 9215 module. This configuration is shown in figure 2.

Additionally, for each part of this experiment, the true temperature was measured via a mercury thermometer.

3.1 Part 1

To gather the room temperature data, the sensors were placed in an unused area in the lab room and left to sit for a few minutes without anyone moving near them or touching them. This was to stop heat from diffusing through the rubber casing of the wire or through the air. The LabVIEW simulation was run for 3 minutes at 1000hz and the data was saved to the Excel file. The results of the simulation are shown in the figures below.

3.2 Part 2

3.2.1 Part 2a: Hot Water

An electric kettle was used to heat up water to near boiling. The LabVIEW simulation was started with the sensors in the ambient environment until the graphs appeared to reach steady-state, which acts as an asymptote on the value from the sensors, and then were abruptly submerged in the boiling water. They stayed in the water until the graph once again appeared at steady-state. This experiment was run over 2 minutes and at a frequency of 1000hz. The region between the two steady-states will be used to calculate the time-constant.

3.2.2 Part 2b: Water Cooling

For this part of the experiment, the collector block's size was changed to one million samples to account for the amount of time it would take for the water to cool from its initial boiling state to a safe and drinkable condition. At a frequency of 1000hz, this gave us approximately 16 minutes of data collection. The sensors were placed in the boiling water and the data was collected until the true temperature, measured via a thermometer, was at $40°C$, as that is the optimal temperature for safe drinking water.

3.2.3 Part 2c: Ice-Hot

Place the three sensors in a bowl of ice-cold water, wait for the graphs to reach equilibrium, and then quickly take them out of the ice water, and into the hot water, measuring until it reaches steady-state. The region between the equilibrium in ice water and the equilibrium in hot water is the time constant we are measuring. In our experiment, the ice water was at $40°C$ and the hot water was at $87°C$.

3.2.4 Part 2d: Quick Changes

Lastly, after the sensor had reached steady state in the water above, we took the sensors out of the water and measured the time it takes for the sensors to return to room temperature. We saved the data to an Excel file with a frequency of 1000 hz.

3.2.5 Part 2e: Sensor Repetition

The data was measured simultaneously for each sensor.

4 Data Processing

Variables

i. N = Number of Samples
ii. f_s = Sampling Frequency, s^{-1}
iii. Δt_s = Sampling Interval, s
iv. γ = Confidence Level, %
v. R_S = Sensor Resistance, Ohms = Ω (In this experiment it will be 1kΩ)
vi. V_S = Source voltage, Volts = V (5 V for this experiment)
vii. R_T = Themistor resistance, Ω

Equations

I. Sample Mean: $\bar{x} = \dfrac{1}{N}\sum_{i=1}^{N} x_i$

II. Standard Deviation of finite N, normalized by $N-1$: $S_x = \sqrt{\sum_{i=1}^{N}\dfrac{(x_i-\bar{x})^2}{N-1}}$

III. Standard Deviation of the Mean: $\dfrac{S_x}{\sqrt{N}}$

IV. Average Measurement w/ Confidence Interval: $\bar{x} \pm t_{stat}\cdot\dfrac{S_x}{\sqrt{N}}$

V. *Steinhart-Hart Relation*: $\dfrac{1}{T} = A + B\cdot ln(R_T) + C\cdot(ln(R_T))^3$, where A, B, C are the Thermistor's calibration coefficients.

Conversion and Calibration

The IC/TMP36 sensor originally outputs voltage. This was converted to $°C$ by taking the IC TMP36 output, say x_V (V for volt), and converting by $x_{°C} = 100\cdot(x_V - 0.5)$. This conversion comes from the TMP36 datasheet ($10\,mV/°C$ w/ $500\,mV$ offset):

Table 4. TMP35/TMP36/TMP37 Output Characteristics

Sensor	Offset Voltage (V)	Output Voltage Scaling (mV/°C)	Output Voltage at 25°C (mV)
TMP35	0	10	250
TMP36	0.5	10	750
TMP37	0	20	500

We utilize **Eq.(V)** to calibrate the Thermistor.

Thermistor Calibration:

$$T = \frac{1}{A + B \cdot ln(R_T) + C \cdot (ln(R_T))^3}$$

By gathering the Thermistor's resistance along with the temperature in each environment we can set up and solve a system of linear equations as shown below:

$$\begin{bmatrix} 1 & ln(R_{T_1}) & (ln(R_{T_1}))^3 \\ 1 & ln(R_{T_2}) & (ln(R_{T_2}))^3 \\ 1 & ln(R_{T_3}) & (ln(R_{T_3}))^3 \end{bmatrix} \cdot \begin{bmatrix} A \\ B \\ C \end{bmatrix} = \begin{bmatrix} \frac{1}{T_1+273.15} \\ \frac{1}{T_2+273.15} \\ \frac{1}{T_3+273.15} \end{bmatrix}$$

Temperature is converted to Kelvin for calculation purposes. This temperature is the (approximate) true measurement. The 1,2,and 3 subscripts represent the three environments (in no particular order).

Mean Temperature in Laboratory w/ Confidence Interval

Calculation of the mean temperature with confidence interval of $\gamma = 95\%$ was implemented through MATLAB as shown below:

```
% Confidence Interval in Laboratory
gamma = 0.95; %95 percent confidence

Fz = 0.5*(1+gamma);

nu = Q-1; %DOF, where Q is the # of samples

p = (1-gamma)/2; %probability

tstat = tinv(p,nu);

% (SAMPLE MEANS) Mean w/ Confidence Interval
avg_unc_thermistor = [mean(thermistordata)
                      tstat*std(thermistordata)/sqrt(Q)];

avg_unc_IC = [mean(ICdata)
              tstat*std(ICdata)/sqrt(Q)];

avg_unc_thermocouple = [mean(thermocoupledata)
                        tstat*std(thermocoupledata)/sqrt(Q)];
```

We define $F(z) = \frac{1}{2}(1+\gamma) = 0.9750$. The degrees of freedom (D.O.F.) $\nu = N - 1 = 59,999$ where $N = 60,000$ samples. Set $P = \dfrac{1-\gamma}{2} = 0.0250$. Using MATLAB function *tinv*, we calculate the t-statistic to be $t_{stat} = -1.960$ or according to the t-distribution tables this is also just $t_{stat} = 1.960$.

Below are the average temperatures w/ the confidence interval for each of the three sensors:

- Thermistor: $1.1743 \pm 0.0001\ V$

	Ambient	Cold	Hot
Temperature (°C)	20.6	4.5	86.3
Voltage (V)	1.8428	2.5041	0.3188
Resistance ($k\Omega$)	0.8639	1.4849	0.1008

Table 1: Caption

- IC/TMP36: 20.8415 ± 0.0038 °C
- Thermocouple: 21.6671 ± 0.0005 °C

5 Results

This section analyzes the results of our data for the three temperature sensors in each environment.

The values in table 1 are gathered from parts a-d of the experiment, and alongside Eq. (5), are used to calibrate the thermistor from voltages to output temperature.

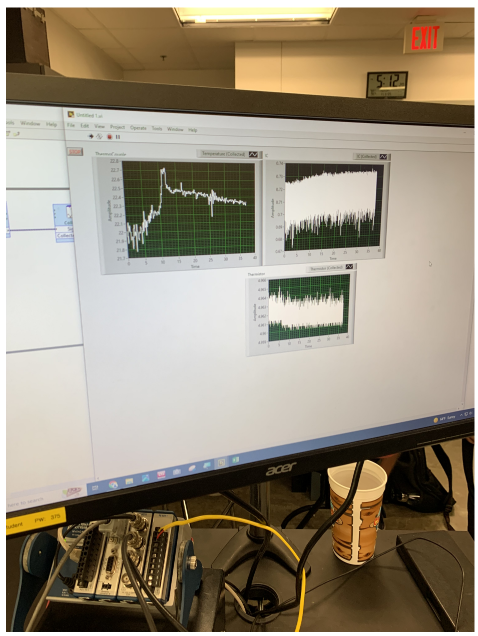

Figure 5: Plotting data on LabVIEW

5.1 Part 1: Ambient Temperature

In Part 1 of the experiment we take measurements of the laboratory room temperature using each of the three sensors: thermocouple, thermistor, and IC TMP36. The data displayed below shows the temperature sensors at work for 1 minute of sampling at $f_s = 1000\ s^{-1}$. This means $\Delta t_s = (f_s \cdot 60)^{-1} = 1.6667 \times 10^{-5}$ minutes.

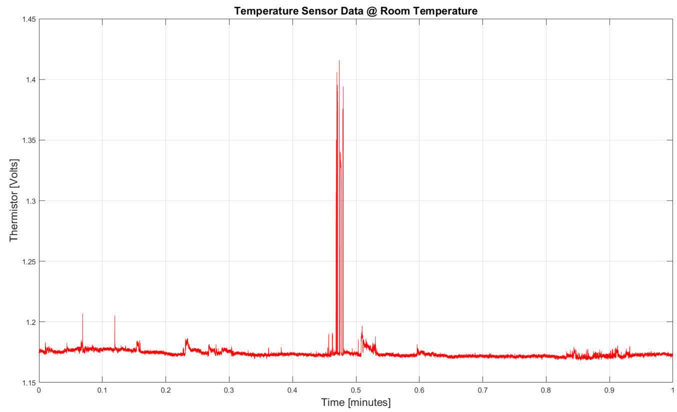

Figure 6: Thermistor at ambient temperature

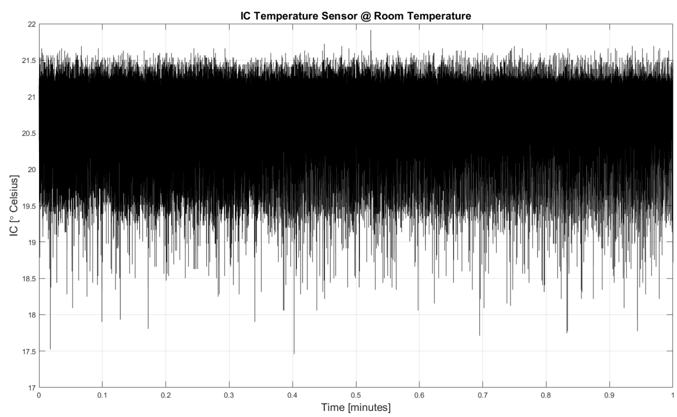

Figure 7: IC TMP36 at ambient temperature

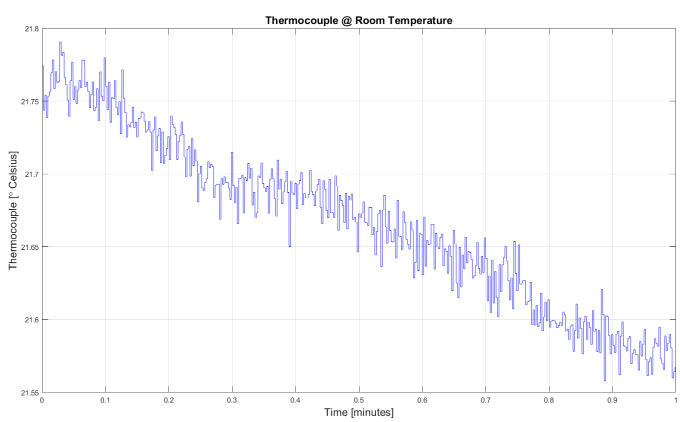

Figure 8: Thermocouple at ambient temperature

There are small spikes occurring around half of the period for the Thermistor's output. This disturbance

	Mean (°C)	Standard Dev. (°C)	95% Confidence Interval	Bias Error (%)	Percent Error (%)
Thermocouple	21.6671	0.0578	0.0005	-	-
IC Sensor	20.8415	0.4722	0.0038	-	-
Thermistor	20.6000	0.0653	4.9328E-04	-	-

Table 2: Part 1 Values for the ambient temperature measurements

	Part a	Part b	Part c	Part d
Initial Temp (To)	t11	t12	t13	t14
Final Temp (Tf)	t21	t22	t23	t24
Time (t)	t31	t32	t33	t34
T at t=tau	t41	t42	t43	t44
time constant (Tau)	t51	t52	t53	

Table 3: Thermocouple Data

could have been due to the Thermistor's sensitivity to very small changes in temperature, possibly due to slight movement (increased kinetic energy correlates to increased thermal energy).

The TMP36 data appears similar to a white noise response for the entirety of the 1 minute period with its large temperature interval. This shows the inaccuracy of the TMP36 when comparing to the other two sensors.

Similar to the small change in the Thermistor's output, the Thermocouple sees small changes as it is decreasing to a steady-state.

Part 1

At ambient room temperatures, all three sensors reported temperatures within xxx% of the true temperature, which was 20.8°C. The BLANK SENSOR had the most accurate readings, and the BLANK SENSOR was the most precise.

Part 2:

The time constant, τ, is defined as the time it takes for the system to change from its original state by 63.2%. For a first order sensor, Equation xx is used. The time constant is measured from steady-state before a step input until the sensor reaches steady-state again. Therefore To will be the initial steady-state temperature and Tf will be the final steady-state temperature after the step input. At a time T=tau, the equation becomes The equation can be written in LaTeX as: $T_\tau = \pm 0.632|T_f - T_o| + T_o$ (+/- depends on increase/decrease in temp)

After taking the data for Part 1, the thermistor data only gave 4.9V for the remainder of the experiments. It is unknown what happened between Part 1 and Part 2, but all data concerning the thermistor for this section is invalid.

Part 2a

	Part a	Part b	Part c	Part d
Initial Temp (To)	t11	t12	t13	t14
Final Temp (Tf)	t21	t22	t23	t24
Time (t)	t31	t32	t33	t34
T at t=tau	t41	t42	t43	t44
time constant (Tau)	t51	t52	t53	

Table 4: IC Sensor Data

As in part 1, the ambient temperature was very similar for all 3 sensors. The time it took for each sensor to reach steady-state after being inserted in the boiling water took longer for the XXX sensor than it did for the XXX sensor. The XXX sensor was the closest to the true temperature of the boiling water and the XXX was the least accurate.

Part 2b

For each sensor, the starting temperature was within X °C of each other, and each sensor took over X seconds to reach a temperature of X degrees. The XX sensor took the shortest, the XX sensor was the longest, but they were still within X seconds of each other. This data produced a linear graph, which can be attributed to the slow temperature change, rather than a sudden spike.

Part 2c

In cold temperatures, the sensors were within X% of the true temperature, with the XX being the most accurate, and the XX being the least. After the sudden temperature change, they were within X% of the true temperature. As shown in table XX, during the sudden temperature changes, the time constant was XX, which is **different / the same** as in part a.

Part 2d

Once again, the steady-states of the hot water were within X°C of each other. The time it took for the sensors to reach the True temperature of the room ranged from X seconds for the XX sensor to X seconds for the XX sensor. The time constants for this experiment are (different / the same) as in part a. This is because

Part 2e

When comparing parts a and d, when the sensors are submerged into the water, the reaction is much faster compared to when the sensors are pulled out into the air. A similar concept arises in part b, when the sensors slowly measure the temperature decrease of the water over time. Water has a much larger specific heat compared to air, which allows for better retention of the heat, and also allows for a more rapid reaction when introduced to a sudden change in temperature.

6 Conclusion

The first goal of this lab was to learn about three different temperature sensors: Thermocouples, IC Sensors, and Thermistors. The thermocouple and IC Sensor report voltage changes as a response to temperature changes, whereas the Thermistor uses resistance. The outputted voltage data was calibrated and converted into usable temperature data through equations given in lectures. The IC Sensor linearly changed in voltage as the temperature changed linearly. The thermistor has an inversely proportional relationship because it uses resistance rather than voltage. Our data for the IC sensor and thermocouple supported this, but the lack of valid data for the thermistor in Part 2 left us unable to quantify this relationship.

The second goal of this lab was the acquire and process data in the LabVIEW software. After the lab session, each group member can comfortably recreate this experiment. This includes the physical circuits and connections, as well as the block diagrams and data collection via LabVIEW. However, it is unknown what the cause is for the lack of valid thermistor data. It could be a simple wire becoming loose as someone moved the breadboard, or it could be a software related issue.

The final goal of this lab was to investigate the transient behavior of a thermistor (first-order sensor). We were unable to properly complete this task. For a majority of the Part 2 experiments, the thermistor graphs should have looked like logarithmic curves, with a fast rate of change initally before slowing down towards the end.

Disregarding the obvious thermistor errors, the rest of the data satisfied every 95% confidence interval. This data showed that the most accurate sensor compared to the true mean was the IC Sensor, with the thermocouple having higher precision.

Appendices

Appendix: t-Distribution Tables

Table A11. *t*-Distribution

Values of z for given values of the distribution function $F(z)$ (cf. p. 754).
Example: For 9 degrees of freedom, $z = 1.83$ when $F(z) = 0.95$.

$F(z)$	Number of Degrees of Freedom									
	1	2	3	4	5	6	7	8	9	10
0.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.6	0.33	0.29	0.28	0.27	0.27	0.27	0.26	0.26	0.26	0.26
0.7	0.73	0.62	0.58	0.57	0.56	0.55	0.55	0.55	0.54	0.54
0.8	1.38	1.06	0.98	0.94	0.92	0.91	0.90	0.89	0.88	0.88
0.9	3.08	1.89	1.64	1.53	1.48	1.44	1.42	1.40	1.38	1.37
0.95	6.31	2.92	2.35	2.13	2.02	1.94	1.90	1.86	1.83	1.81
0.975	12.7	4.30	3.18	2.78	2.57	2.45	2.37	2.31	2.26	2.23
0.99	31.8	6.97	4.54	3.75	3.37	3.14	3.00	2.90	2.82	2.76
0.995	63.7	9.93	5.84	4.60	4.03	3.71	3.50	3.36	3.25	3.17
0.999	318.3	22.3	10.2	7.17	5.89	5.21	4.79	4.50	4.30	4.14

$F(z)$	Number of Degrees of Freedom									
	11	12	13	14	15	16	17	18	19	20
0.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.6	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.26
0.7	0.54	0.54	0.54	0.54	0.54	0.54	0.53	0.53	0.53	0.53
0.8	0.88	0.87	0.87	0.87	0.87	0.87	0.86	0.86	0.86	0.86
0.9	1.36	1.36	1.35	1.35	1.34	1.34	1.33	1.33	1.33	1.33
0.95	1.80	1.78	1.77	1.76	1.75	1.75	1.74	1.73	1.73	1.73
0.975	2.20	2.18	2.16	2.15	2.13	2.12	2.11	2.10	2.09	2.09
0.99	2.72	2.68	2.65	2.62	2.60	2.58	2.57	2.55	2.54	2.53
0.995	3.11	3.06	3.01	2.98	2.95	2.92	2.90	2.88	2.86	2.85
0.999	4.03	3.93	3.85	3.79	3.73	3.69	3.65	3.61	3.58	3.55

$F(z)$	Number of Degrees of Freedom									
	22	24	26	28	30	40	50	100	200	∞
0.5	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
0.6	0.26	0.26	0.26	0.26	0.26	0.26	0.26	0.25	0.25	0.25
0.7	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.53	0.52
0.8	0.86	0.86	0.86	0.86	0.85	0.85	0.85	0.85	0.84	0.84
0.9	1.32	1.32	1.32	1.31	1.31	1.30	1.30	1.29	1.29	1.28
0.95	1.72	1.71	1.71	1.70	1.70	1.68	1.68	1.66	1.65	1.65
0.975	2.07	2.06	2.06	2.05	2.04	2.02	2.01	1.98	1.97	1.96
0.99	2.51	2.49	2.48	2.47	2.46	2.42	2.40	2.37	2.35	2.33
0.995	2.82	2.80	2.78	2.76	2.75	2.70	2.68	2.63	2.60	2.58
0.999	3.51	3.47	3.44	3.41	3.39	3.31	3.26	3.17	3.13	3.09