

Precision RTD Instrumentation for Temperature Sensing

Author: Ezana Haile
Microchip Technology Inc.

INTRODUCTION

Precision RTD (Resistive Temperature Detector) instrumentation is key for high performance thermal management applications. This application note shows how to use a high resolution Delta-Sigma Analog-to-Digital converter, and two resistors to measure RTD resistance ratiometrically. A $\pm 0.1^\circ\text{C}$ accuracy and $\pm 0.01^\circ\text{C}$ measurement resolution can be achieved across the RTD temperature range of -200°C to $+800^\circ\text{C}$ with a single point calibration.

A high resolution Delta-Sigma ADC can serve well for high performance thermal management applications such as industrial or medical instrumentation. Traditionally, RTDs are biased with a constant current source. The voltage drop across the RTD is conditioned using an Instrumentation Amplifier which requires multiple resistors, capacitors and few operation amplifiers and/or a stand-alone instrumentation amplifier. This analog instrumentation technique requires a low noise and stable system to calibrate and accurately measure temperature. It also requires an operator for optimization on the production floor. With the Delta-Sigma ADC solution, the RTD is directly connected to the ADC (Microchip's MCP3551 family of 22 bit Delta-Sigma ADCs) and a single low tolerance resistor is used to bias the RTD from the ADC reference voltage (Figure 1) and accurately measure temperature ratiometrically. A low drop out linear regulator (LDO) is used to provide a reference voltage.

SOLUTION

This solution uses a common reference voltage to bias the RTD and the ADC which provides a ratio-metric relation between the ADC resolution and the RTD temperature resolution. Only one biasing resistor, R_A , is needed to set the measurement resolution ratio (Equation 1).

EQUATION 1: RTD RESISTANCE

$$R_{RTD} = R_A \left(\frac{\text{Code}}{2^{n-1} - \text{Code}} \right)$$

Where:

- Code = ADC output code
- R_A = Biasing resistor
- n = ADC number of bits (22 bits with sign, MCP3551)

For instance, a 2V ADC reference voltage (V_{REF}) results in a $1 \mu\text{V}/\text{LSb}$ (Least Significant Bit) resolution. Setting $R_A = R_B = 6.8 \text{ k}\Omega$ provides $111.6 \mu\text{V}/^\circ\text{C}$ temperature coefficient (PT100 RTD with $0.385\Omega/^\circ\text{C}$ temperature coefficient). This provides $0.008^\circ\text{C}/\text{LSb}$ temperature measurement resolution for the entire range of 20Ω to 320Ω or -200°C to $+800^\circ\text{C}$. A single point calibration with a 0.1% 100Ω resistor provides $\pm 0.1^\circ\text{C}$ accuracy as shown in Figure 1.

This approach provides a plug-and-play solution with minimum adjustment. However, the system accuracy depends on several factors such as the RTD type, biasing circuit tolerance and stability, error due to power dissipation or self-heat, and RTD non-linear characteristics.

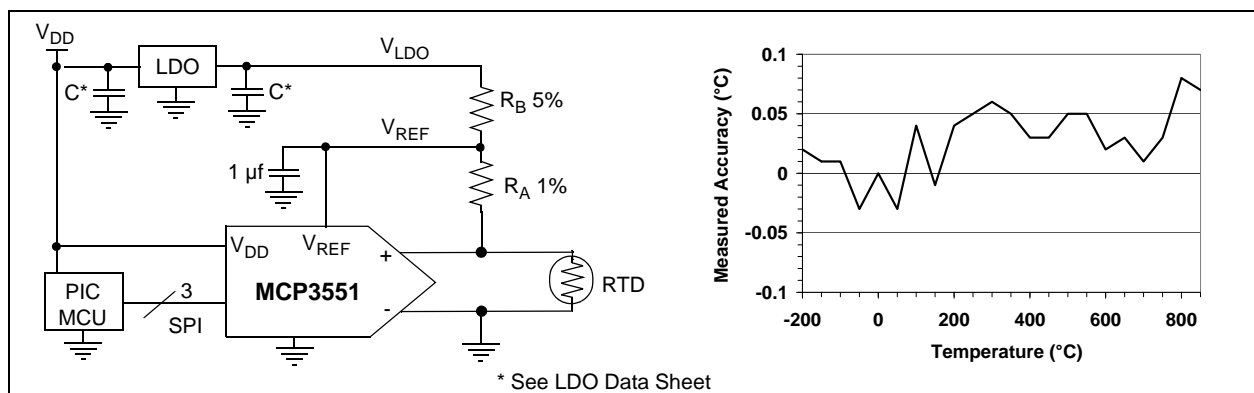


FIGURE 1: RTD Instrumentation Circuit Block Diagram and Output Performance [3].

Ratiometric Measurement

The key feature of a ratiometric measurement technique is that the temperature accuracy does not depend on an accurate reference voltage. The ADC reference voltage varies with respect to change in RTD resistance due to the voltage divider relation (Equation 2). This measurement maintains constant resolution. It eliminates the need for a constant biasing current source or a voltage source, which can be costly, while providing a highly accurate temperature measurement solution. Figure 2 shows circuit block diagram with the ADC reference.

EQUATION 2: REFERENCE VOLTAGE

$$V_{REF} = \frac{R_A + R_{RTD}}{R_A + R_B + R_{RTD}} V_{DD}$$

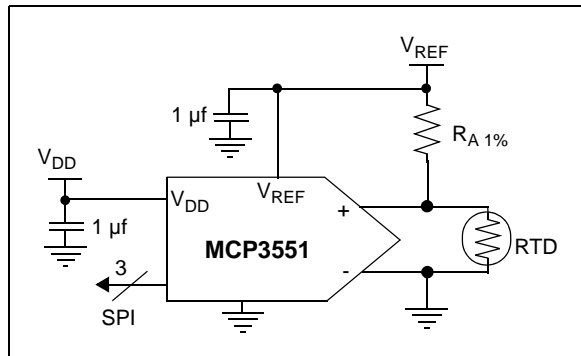


FIGURE 2: RTD Biasing Circuit.

R_A and R_B must be sufficiently large to minimize error due to selfheat while providing adequate measurement resolution.

Equation 3 and Equation 4 show that due to the ratiometric relation V_{REF} and R_B cancel. They do not influence the code to RTD-resistance conversion. This equation can be easily implemented using a 16-bit microcontroller such as PIC18F family.

EQUATION 3: VOLTAGE ACROSS RTD

$$V_{RTD} = V_{REF} \left(\frac{R_{RTD}}{R_A + R_{RTD}} \right) = V_{REF} \left(\frac{Code}{2^{n-1}} \right)$$

Where:

- V_{RTD} (V) = RTD voltage
- V_{REF} (V) = Reference Voltage
- Code = ADC output code
- n = ADC number of bits (22 bits with sign, MCP3551)

Solving for R_{RTD} from Equation 3 gives:

EQUATION 4: RTD RESISTANCE AND ADC CODE RELATIONS

$$R_{RTD} = R_A \left(\frac{Code}{2^{n-1} - Code} \right)$$

Measurement Resolution and ADC Characteristics

EQUATION 5: ADC RESOLUTION

$$ADC_{RESOLUTION} = \frac{V_{REF}}{2^{(n-1)}}$$

Where:

- V_{REF} (V) = Reference Voltage
- n = ADC number of bits (22 bits with sign, MCP3551)

The key element to this solution is the direct proportionality of ΔADC_{LSb_quanta} and ΔR_{RTD} . The temperature measurement resolution can be determined as shown in Equation 6.

EQUATION 6: TEMPERATURE MEASUREMENT RESOLUTION

$$T_{RES} = \frac{ADC_{RESOLUTION}}{\Delta V_{RTD}}$$

Where:

- T_{RES} (°C/LSb) = Temperature Measurement Resolution

When $R_A = R_B = 6800\Omega$, the bias current is ~290 μ A. This provides < 0.01°C/LSb temperature resolution. As the RTD resistance varies due to temperature, the I_{BIAS} (biasing current) varies and temperature resolution remains below 0.01°C/LSb as shown in Figure 3.

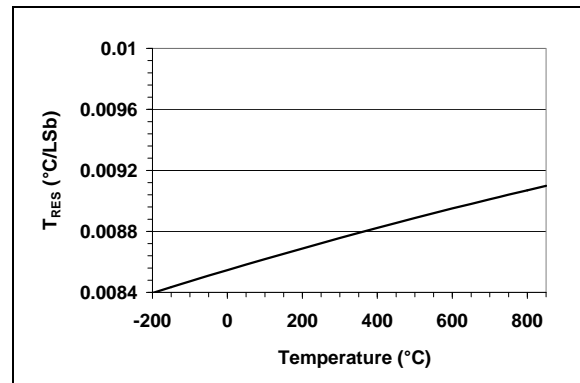


FIGURE 3: T_{RES} vs. RTD Resistance.

The MCP3551 22-bit differential ADC characteristics is optimum for this type of application. There are few specifications that must be carefully considered, such as conversion accuracy and noise performance. The maximum full scale error of the MCP3551 is 10 ppm and the error drift is 0.028 ppm/C. The maximum Integral Non-linearity is 6 ppm. These specifications are so minute when considering the overall effect to temperature measurement accuracy. If I_{BIAS} is set to $\sim 300 \mu A$, then the input voltage range to the ADC is $\sim 100 mV$ (V_{RTD}) over the entire RTD temperature range. Therefore, the error is much less than the full scale error specified in the ADC datasheet.

However, the input offset noise is $2.5 \mu V$ (typical) and $6 \mu V$ (typical) for MCP3551 and MCP3553 ADCs, respectively. This specification adds offset error that needs be considered when converting temperature. The offset error is specified as $12 \mu V$ (maximum) at $+25^\circ C$. This means there is up to 12 LSB flicker or the temperature measurement precision is $0.09^\circ C$ maximum (Equation 6). This can be improved by taking the average of multiple samples to precisely determine temperature.

R_A Tolerance and Measurement Accuracy

The variation in R_A characteristics introduces temperature accuracy error. A 1% tolerance in R_A produces a $20^\circ C$ error and a 0.1% tolerance produces a $2^\circ C$ error. For lower tolerance resistors, R_A must be calibrated for precision temperature measurements.

In order to precisely calibrate R_A , a calibration resistor can be used in place of the RTD, such as 100Ω 0.1% tolerance resistor and Equation 4 can be rearranged to determine R_A .

RTD Temperature Calculation

RTDs are significantly non-linear. Depending on the RTD type and specification, the resistor to temperature conversion equations have been defined and standardized. The equation for the PT100 RTD can be found at American Society for Testing and Materials (ASTM) [1] specification number E1137E.

Figure 4 shows the error that occurs by ignoring the 2nd and higher power errors from RTD.

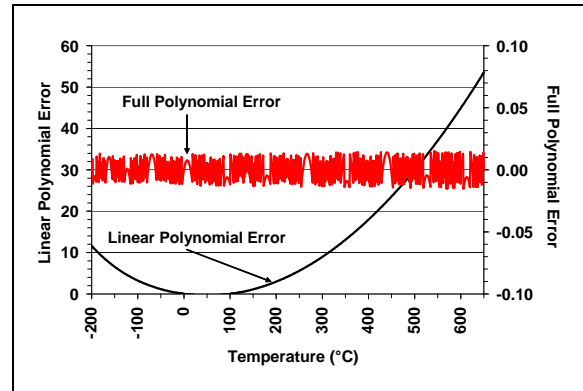


FIGURE 4: RTD to Temperature Conversion Error.

Power Supply Noise

Another source of error is the system power supply. Most power supplies for portable systems use switching regulators which generates high frequency glitches at the switching frequency of typically 100 kHz. Other sources of noise include digital switching from system processor or system oscillator. This high frequency noise can couple throughout system and directly influence the measurement accuracy. Therefore, high performance sensor applications require analog filters.

The power supply voltage, V_{DD} , connected to the input of the LDO must be filtered using Resistor Capacitor network (RC network) with low corner frequency, approximately 1 kHz. The filtered voltage can be set to a desired level using a low dropout linear regulator (LDO). Refer to the LDO datasheet for dropout voltage specification when setting the LDO output voltage. Figure 1 show a typical configuration. The two RC filters provide 40 dB per decade rolloff.

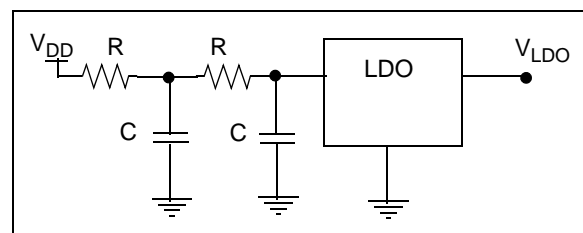


FIGURE 5: RTD Biasing Circuit.

Note that the RC filter is applied before the LDO. Typically, the Power Supply Rejection Ratio (PRSS) of an LDO is ~ 0 dB at higher frequencies. Therefore, It is necessary to filter the input voltage to prevent the noise coupling through the LDO to the ADC and RTD.

In addition, when designing PCB layout, avoid placing digital signal traces in close proximity to the RTD biasing circuit.

AN1154

Effect of RTD Self-heat Due to Power Dissipation

When biasing RTD, self-heat due to power dissipation can compromise system accuracy. The effect of Self-heat can be reduced by reducing the biasing current magnitude. The current magnitude needs to be sufficiently low to reduce self-heat while providing adequate voltage range and measurement resolution. Ideally, the added temperature due to self-heat must be lower than the temperature measurement resolution, T_{RES} (Equation 6).

To determine error due to self-heat, refer to the RTD datasheet for Self-heat coefficient specification in degree Celsius per milli-watt ($^{\circ}\text{C}/\text{mW}$). This coefficient is used to convert heat due to power dissipation to temperature. For example, a small surface mount PT100 RTD with $0.2^{\circ}\text{C}/\text{mW}$ self-heat coefficient would dissipate 0.002°C with $300\ \mu\text{A}$ bias current at 0°C (100Ω), and 0.006°C at high temperature (350Ω). In

this case, the maximum heat dissipated due to self-heat is less than 0.008°C T_{RES} . Therefore, error due to self heat is not measurable.

EQUATION 7: RTD POWER

$$P_{RTD} = \frac{V_{RTD}}{R_{RTD}}$$

Where:

$$P_{RTD} \text{ (Watt)} = \text{Power across RTD}$$

Test Result

This approach was validated using Microchip's MCP3551 ADC device [3] as shown in Figure 1.

The ratiometric solution was used with a calibrated RTD simulator [4] to generate the data as shown in Table 1. The graph in Figure 1 shows that the ratiometric relation provides the highest accuracy.

TABLE 1: RATIOMETRIC TEST RESULTS USING AN RTD SIMULATOR

Ratiometric Measurement				
Temperature ($^{\circ}\text{C}$)	Resistance (Ω)		Measured Temperature – Full Polynomial ($^{\circ}\text{C}$)	Measurement Error ($^{\circ}\text{C}$)
	Actual	Measured		
-200	18.52	18.51	-200.02	0.02
-150	39.72	39.72	-150.01	0.01
-100	60.26	60.25	-100.01	0.01
-50	80.31	80.32	-49.97	-0.03
0	100	100	0	0
50	119.4	119.41	50.03	-0.03
100	138.51	138.49	99.96	0.04
150	157.33	157.33	150.01	-0.01
200	175.86	175.84	199.96	0.04
250	194.1	194.08	249.95	0.05
300	212.05	212.03	299.94	0.06
350	229.72	229.7	349.95	0.05
400	247.09	247.08	399.97	0.03
450	264.18	264.17	449.97	0.03
500	280.98	280.96	499.95	0.05
550	297.49	297.47	549.95	0.05
600	313.71	313.7	599.98	0.02
650	329.64	329.61	649.97	0.03
700	345.28	345.28	699.99	0.01
750	360.64	360.6	749.97	0.03
800	375.7	375.68	799.92	0.08
850	390.48	390.45	849.93	0.07

CONCLUSION

Microchip's MCP3551 differential ADC is ideal for high performance thermal management applications. This application note discusses an RTD application which uses a ratiometric relation between the ADC LSB quanta and the RTD temperature coefficient. This was achieved using low tolerance resistor and a reference voltage to bias the RTD and ADC and measure temperature ratiometrically with 0.01°C temperature resolution from -200°C to 800°C temperature range. A 0.1°C accuracy can be achieved using a single point calibration.

This approach eliminates the need for a high-performance RTD systems that require constant current source and complex instrumentation systems. This technique provides a low cost, high performance, plug and play solution for all RTDs.

REFERENCE

1. www.astm.com
2. National Institutes of Standards and Technology (NIST)
3. RTD Demonstration Board
(estimated release in June 2008)
4. OMEGA RTD Simulator, CL510-7.
5. MCP3550/1/3 Data Sheet, "Low-Power Single Channel 22-Bit Delta Sigma ADCs", DS21950, ©2007, Microchip Technology Inc.

AN1154

NOTES:

Note the following details of the code protection feature on Microchip devices:

- Microchip products meet the specification contained in their particular Microchip Data Sheet.
- Microchip believes that its family of products is one of the most secure families of its kind on the market today, when used in the intended manner and under normal conditions.
- There are dishonest and possibly illegal methods used to breach the code protection feature. All of these methods, to our knowledge, require using the Microchip products in a manner outside the operating specifications contained in Microchip's Data Sheets. Most likely, the person doing so is engaged in theft of intellectual property.
- Microchip is willing to work with the customer who is concerned about the integrity of their code.
- Neither Microchip nor any other semiconductor manufacturer can guarantee the security of their code. Code protection does not mean that we are guaranteeing the product as “unbreakable.”

Code protection is constantly evolving. We at Microchip are committed to continuously improving the code protection features of our products. Attempts to break Microchip's code protection feature may be a violation of the Digital Millennium Copyright Act. If such acts allow unauthorized access to your software or other copyrighted work, you may have a right to sue for relief under that Act.

Information contained in this publication regarding device applications and the like is provided only for your convenience and may be superseded by updates. It is your responsibility to ensure that your application meets with your specifications. MICROCHIP MAKES NO REPRESENTATIONS OR WARRANTIES OF ANY KIND WHETHER EXPRESS OR IMPLIED, WRITTEN OR ORAL, STATUTORY OR OTHERWISE, RELATED TO THE INFORMATION, INCLUDING BUT NOT LIMITED TO ITS CONDITION, QUALITY, PERFORMANCE, MERCHANTABILITY OR FITNESS FOR PURPOSE. Microchip disclaims all liability arising from this information and its use. Use of Microchip devices in life support and/or safety applications is entirely at the buyer's risk, and the buyer agrees to defend, indemnify and hold harmless Microchip from any and all damages, claims, suits, or expenses resulting from such use. No licenses are conveyed, implicitly or otherwise, under any Microchip intellectual property rights.

Trademarks

The Microchip name and logo, the Microchip logo, Accuron, dsPIC, KEELOQ, KEELOQ logo, MPLAB, PIC, PICmicro, PICSTART, PRO MATE, rPIC and SmartShunt are registered trademarks of Microchip Technology Incorporated in the U.S.A. and other countries.


AmpLab, FilterLab, Linear Active Thermistor, MXDEV, MXLAB, SEEVAL, SmartSensor and The Embedded Control Solutions Company are registered trademarks of Microchip Technology Incorporated in the U.S.A.

Analog-for-the-Digital Age, Application Maestro, CodeGuard, dsPICDEM, dsPICDEM.net, dsPICworks, dsSPEAK, ECAN, ECONOMONITOR, FanSense, In-Circuit Serial Programming, ICSP, ICEPIC, Mindi, MiWi, MPASM, MPLAB Certified logo, MPLIB, MPLINK, mTouch, PICkit, PICDEM, PICDEM.net, PICtail, PowerCal, PowerInfo, PowerMate, PowerTool, REAL ICE, rLAB, Select Mode, Total Endurance, UNI/O, WiperLock and ZENA are trademarks of Microchip Technology Incorporated in the U.S.A. and other countries.

SQTP is a service mark of Microchip Technology Incorporated in the U.S.A.

All other trademarks mentioned herein are property of their respective companies.

© 2008, Microchip Technology Incorporated, Printed in the U.S.A., All Rights Reserved.

 Printed on recycled paper.

QUALITY MANAGEMENT SYSTEM
CERTIFIED BY DNV
== ISO/TS 16949:2002 ==

Microchip received ISO/TS-16949:2002 certification for its worldwide headquarters, design and wafer fabrication facilities in Chandler and Tempe, Arizona; Gresham, Oregon and design centers in California and India. The Company's quality system processes and procedures are for its PIC® MCUs and dsPIC® DSCs, KEELOQ® code hopping devices, Serial EEPROMs, microperipherals, nonvolatile memory and analog products. In addition, Microchip's quality system for the design and manufacture of development systems is ISO 9001:2000 certified.



WORLDWIDE SALES AND SERVICE

AMERICAS

Corporate Office
2355 West Chandler Blvd.
Chandler, AZ 85224-6199
Tel: 480-792-7200
Fax: 480-792-7277
Technical Support:
<http://support.microchip.com>
Web Address:
www.microchip.com

Atlanta
Duluth, GA
Tel: 678-957-9614
Fax: 678-957-1455

Boston
Westborough, MA
Tel: 774-760-0087
Fax: 774-760-0088

Chicago
Itasca, IL
Tel: 630-285-0071
Fax: 630-285-0075

Dallas
Addison, TX
Tel: 972-818-7423
Fax: 972-818-2924

Detroit
Farmington Hills, MI
Tel: 248-538-2250
Fax: 248-538-2260

Kokomo
Kokomo, IN
Tel: 765-864-8360
Fax: 765-864-8387

Los Angeles
Mission Viejo, CA
Tel: 949-462-9523
Fax: 949-462-9608

Santa Clara
Santa Clara, CA
Tel: 408-961-6444
Fax: 408-961-6445

Toronto
Mississauga, Ontario,
Canada
Tel: 905-673-0699
Fax: 905-673-6509

ASIA/PACIFIC

Asia Pacific Office
Suites 3707-14, 37th Floor
Tower 6, The Gateway
Harbour City, Kowloon
Hong Kong
Tel: 852-2401-1200
Fax: 852-2401-3431

Australia - Sydney
Tel: 61-2-9868-6733
Fax: 61-2-9868-6755

China - Beijing
Tel: 86-10-8528-2100
Fax: 86-10-8528-2104

China - Chengdu
Tel: 86-28-8665-5511
Fax: 86-28-8665-7889

China - Hong Kong SAR
Tel: 852-2401-1200
Fax: 852-2401-3431

China - Nanjing
Tel: 86-25-8473-2460
Fax: 86-25-8473-2470

China - Qingdao
Tel: 86-532-8502-7355
Fax: 86-532-8502-7205

China - Shanghai
Tel: 86-21-5407-5533
Fax: 86-21-5407-5066

China - Shenyang
Tel: 86-24-2334-2829
Fax: 86-24-2334-2393

China - Shenzhen
Tel: 86-755-8203-2660
Fax: 86-755-8203-1760

China - Wuhan
Tel: 86-27-5980-5300
Fax: 86-27-5980-5118

China - Xiamen
Tel: 86-592-2388138
Fax: 86-592-2388130

China - Xian
Tel: 86-29-8833-7252
Fax: 86-29-8833-7256

China - Zhuhai
Tel: 86-756-3210040
Fax: 86-756-3210049

ASIA/PACIFIC

India - Bangalore
Tel: 91-80-4182-8400
Fax: 91-80-4182-8422

India - New Delhi
Tel: 91-11-4160-8631
Fax: 91-11-4160-8632

India - Pune
Tel: 91-20-2566-1512
Fax: 91-20-2566-1513

Japan - Yokohama
Tel: 81-45-471- 6166
Fax: 81-45-471-6122

Korea - Daegu
Tel: 82-53-744-4301
Fax: 82-53-744-4302

Korea - Seoul
Tel: 82-2-554-7200
Fax: 82-2-558-5932 or
82-2-558-5934

Malaysia - Kuala Lumpur
Tel: 60-3-6201-9857
Fax: 60-3-6201-9859

Malaysia - Penang
Tel: 60-4-227-8870
Fax: 60-4-227-4068

Philippines - Manila
Tel: 63-2-634-9065
Fax: 63-2-634-9069

Singapore
Tel: 65-6334-8870
Fax: 65-6334-8850

Taiwan - Hsin Chu
Tel: 886-3-572-9526
Fax: 886-3-572-6459

Taiwan - Kaohsiung
Tel: 886-7-536-4818
Fax: 886-7-536-4803

Taiwan - Taipei
Tel: 886-2-2500-6610
Fax: 886-2-2508-0102

Thailand - Bangkok
Tel: 66-2-694-1351
Fax: 66-2-694-1350

EUROPE

Austria - Wels
Tel: 43-7242-2244-39
Fax: 43-7242-2244-393

Denmark - Copenhagen
Tel: 45-4450-2828
Fax: 45-4485-2829

France - Paris
Tel: 33-1-69-53-63-20
Fax: 33-1-69-30-90-79

Germany - Munich
Tel: 49-89-627-144-0
Fax: 49-89-627-144-44

Italy - Milan
Tel: 39-0331-742611
Fax: 39-0331-466781

Netherlands - Drunen
Tel: 31-416-690399
Fax: 31-416-690340

Spain - Madrid
Tel: 34-91-708-08-90
Fax: 34-91-708-08-91

UK - Wokingham
Tel: 44-118-921-5869
Fax: 44-118-921-5820