AN2868
Application note

STM32F10xxx
internal RC oscillator (HSI) calibration

Introduction

The STM32F10xxx microcontrollers offer the possibility of running from an internal RC oscillator (HSI: high-speed internal oscillator of 8 MHz, typically). At 25 °C, the HSI has an accuracy of ±1% typically. In the range of –40 to 105 °C, the accuracy value of the RC frequency increases to the maximum value of ±3%. Temperature therefore has an impact on RC accuracy.

To compensate for the influence of temperature in the application, the output frequency of the STM32F10xxx HSI oscillator can be further trimmed by the user runtime calibration routine to improve the HSI frequency accuracy. This may prove crucial for communication peripherals.

This application note gives two methods of calibrating the internal RC oscillator: finding the frequency with the minimum error or finding the maximum allowed frequency error. Both are implemented by providing an accurate reference source such as an RTC/64 signal or a mains source signal.

Both methods are based on the same technique: computing of the RC frequency vs. the reference frequency, computing of the HSI frequency error and setting of the HSITRIM bits in the RCC_CR register.

Contents

List of tables

List of figures

1 STM32F10xxx’s internal clock: HSI clock

The HSI clock signal is generated from an internal 8 MHz RC oscillator and can be used directly as a system clock or divided by 2 to be used as a PLL input. The HSI RC oscillator has the advantage of providing a clock source at low cost (no external components). It also has a faster startup time than the HSE crystal oscillator. However, even with calibration the frequency is less accurate than an external crystal oscillator or ceramic resonator. The HSI signal can also be used as a backup source (auxiliary clock) if the HSE crystal oscillator fails.

1.1 Calibration

RC oscillator frequencies may vary from one chip to another due to manufacturing process variations. For this reason, each device is factory-calibrated by ST for 1% accuracy at T_A = 25 °C.

After reset, the factory calibration value is loaded into the HSICAL[7:0] bits in the clock control register RCC_CR.

User calibration is performed by setting the HSITRIM[4:0] bits in the RCC_CR register. These bits can be programmed to take into account voltage and temperature variations that affect the frequency of the internal HSI RC oscillator. The default value is 16, which, when added to the HSICAL value, should trim the HSI to 8 MHz ±1%. The trimming step ($F_{hsitrim}$) is around 40 kHz between two consecutive HSICAL steps.

2 RC calibration

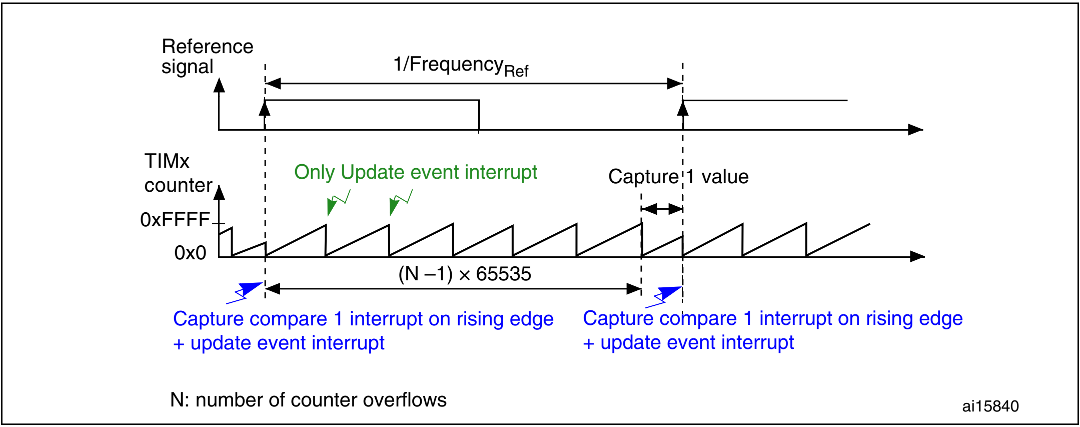
2.1 Principle of calibration

The principle of calibration consists in first measuring the HSI frequency, then computing the frequency error, and finally setting the HSITRIM bits in the RCC_CR register.

The HSI frequency is not measured directly, but it is estimated from the number of HSI clock pulses counted using a timer, and compared to an ideal value: 8 000 000 Hz. To do so, a very accurate reference frequency must be available such as the RTC/64 signal provided by the external 32 kHz crystal or the 50 Hz/60 Hz of the mains (refer to *Section 2.2.2*). In the case of an RTC clock source, the reference frequency is equal to 512 Hz (32768 Hz/64).

Figure 1 shows how the reference signal period is measured in number of timer counts.

Figure 1. Quantification of the reference signal period (RTC signal)


Reference signal
1/FrequencyRef
TIMx counter
Only Update event interrupt
Capture 1 value
0xFFFF
0x0
(N –1) × 65535
Capture compare 1 interrupt on rising edge + update event interrupt
Capture compare 1 interrupt on rising edge + update event interrupt
N: number of counter overflows
ai15840

On each rising edge, two interrupts occur: capture compare 1 interrupt and update event interrupt. The latter is used to count the number of counter overflows over a reference signal period. Since both interrupts occur at the same time at the beginning of every new period, an extra overflow occurs. This is the reason why we have to subtract 1 from the number of counter overflows: N – 1.

Thus the number of counted HSI clock pulses is given as follows:

$\text{TimerPeriodCount} = (N-1)\times 65535 + \text{Capture1}$, where:

– N is the number of timer overflows during one period of the reference frequency

– Capture1 is the value read from the timer CCR1 register.

Since the timer is clocked by the internal RC, the microcontroller can compute the real frequency generated by the HSI versus the reference frequency.

$\text{Frequency}_{RC} = \text{TimerPeriodCount} \times \text{Frequency}_{Ref}$

The error (in Hz) is computed as the absolute value of the difference between the RC frequency (Frequency_{RC}) and 8 000 000 Hz.

Hence the RC frequency error is expressed as:

$\text{Error(Hz)} = |\text{Frequency}_{RC} - 8000000|$.

After calculating the error, the algorithm determines the calibration value that has to be written to the HSITRIM bits in the RCC_CR register (refer to *Section 3* for more details).

2.2 Hardware implementation

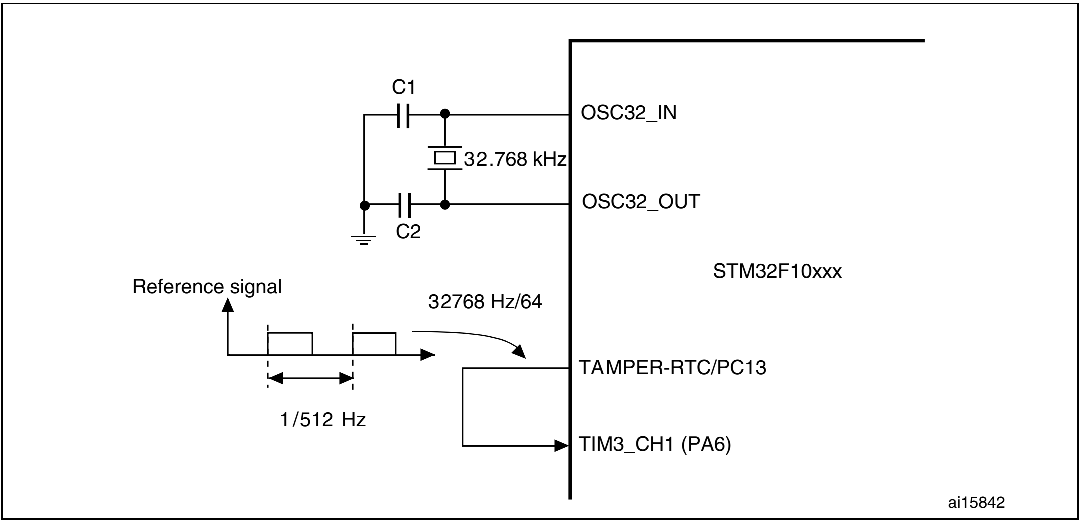
2.2.1 Case where RTC/64 is used as the reference frequency: 512 Hz

The STM32F10xxx can output the RTC signal divided by 64 onto GPIO PC13 (TAMPER-RTC pin). The TAMPER-RTC signal can be used as the reference frequency for RC calibration. For that purpose, this pin must be configured as alternate function push-pull and be connected to a timer channel input.

Note: In the rest of this application note, the channel used will be timer 3 channel 1 (TIM3_CH1).

Figure 2 shows the hardware connections needed for RC calibration using RTC/64 as an accurate frequency source for calibration.

Figure 2. Hardware connection using RTC/64 as a source for calibration



2.2.2 Case where the mains frequency is used as the reference frequency: 50 Hz/60 Hz

This section describes the hardware requirements of the method that uses the AC mains frequency as a reference. *Figure 3* illustrates the circuit implemented to provide the DC power supply (approximately 3.3 V) to the microcontroller:
The only component required to protect the timer input is a resistor. So if no power supply is needed, then only a resistor is needed on the TIM3_CH1 input, to protect the timer input from overcurrents.
This circuit includes a few passive components to convert the 220 V/50 Hz mains of the EU, or the 110 V/60 Hz mains of the US, to a 3.3 V DC power supply. For applications that have higher current consumptions, a power converter could be used (refer to the application note AN1357: VIPower: low cost power supplies using VIPer12A in non isolated applications).

Caution: The reference signal conditioning and power supply circuits cannot be used if there are big current variations.

In case of noisy mains, it is recommended to use an input power line filter (refer to the application note AN2326: Calibrating the RC oscillator of the ST7ULTRALITE MCU using the mains).

Figure 3. Hardware connection in the AC mains calibration method

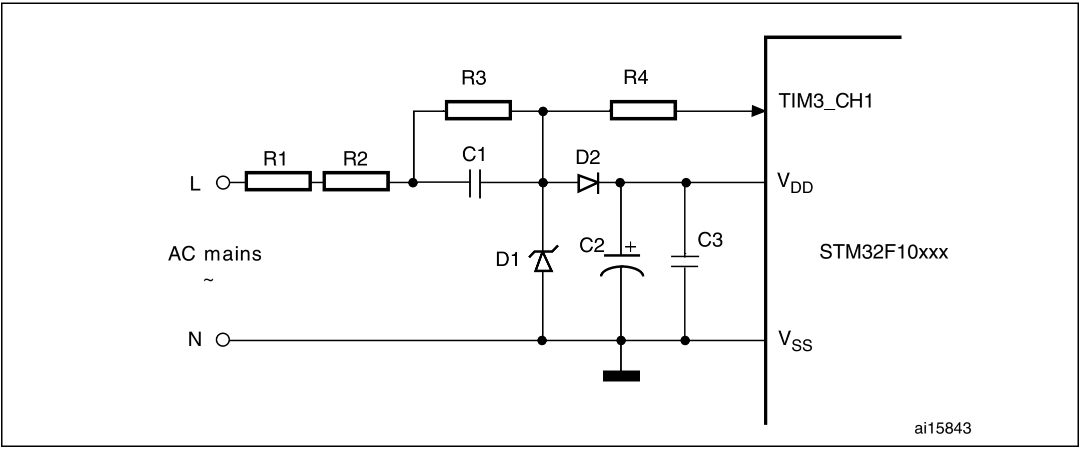


Table 1. Component values when using the mains frequency as the reference

Component	230 V/50 Hz value	110 V/60 Hz value
R1	220 Ω / 0.5 W	110 Ω / 0.5 W
R2	220 Ω / 0.5 W	110 Ω / 0.5 W
R3	1 MΩ	1 MΩ
R4	5.6 kΩ	5.6 kΩ
D1	BZX85C3V9	BZX85C3V9
D2	1N4148	1N4148
C1	470 nF / ~275 V AC	330 nF / ~275 V AC
C2	100 nF	100 nF
C3	470 µF/16 V	470 µF/16 V

3 Description of the RC calibration library

The HSI calibration library provided with this application note includes three major functions:

- `void HSI_FreqMeasure(void)`
- `s32 HSI_CalibrateMinError(void)`
- `ErrorStatus HSI_CalibrateFixedError(u32 AllowedErrorMax, s32* Freq)`

3.1 `HSI_FreqMeasure()` function

This function is called in the timer 3 interrupt handler (`TIM3_IRQHandler()`). The `HSI_FreqMeasure()` function measures the RC frequency after every input signal period. The number of measurement periods is configured by the user in the *HSI_calibration.h* file as follows:

```
#define NbOfPeriod       10 /* Number of period to be measured = 10 */
```

If the number of periods reaches the `NbOfPeriod` number, the `HSI_FreqMeasure()` function computes the average of all measured frequencies (`NbOfPeriod` measured frequencies).

The averaging method is used to minimize frequency error measurements.

You can easily configure the frequency of the reference source. It is defined in the file *HSI_calibration.h* as follows:

```
#define Ref_Frequency 512 /* The reference frequency value in hertz */
```

If the reference frequency is a mains source frequency equal to 50 Hz, then replace 512 by 50 in the previous line as shown below:

```
#define Ref_Frequency 50 /* The reference frequency value in hertz */
```

If RTC/64 is used as the reference frequency, uncomment the following line:

```
#define USE_Reference_RTC
```

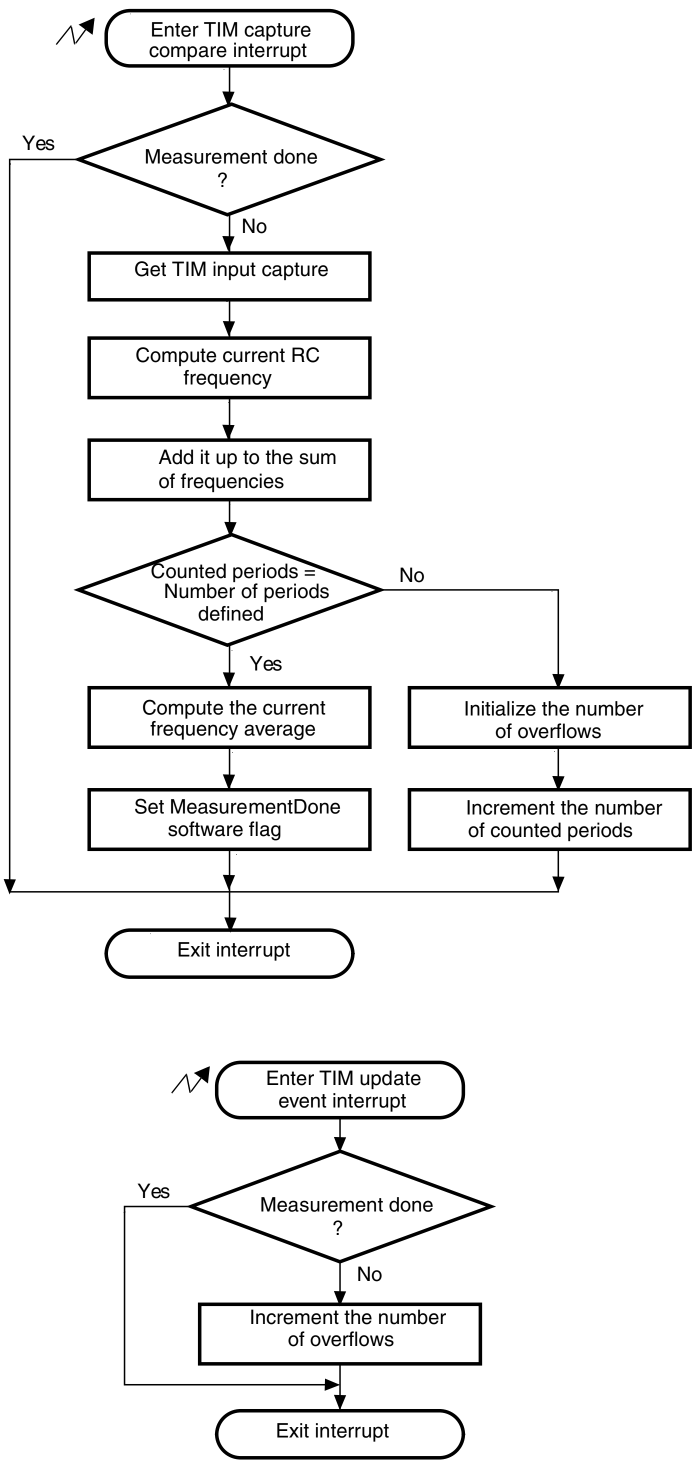
If another reference is used, such as the mains, comment the previous line. In so doing, the RTC and the PC13 pin will be not configured while the system is configured for calibration.

After the frequency averaging computation, the MeasurementDone software flag is set to ‘1’ to indicate that the frequency measurements are finished and that the process is ready for the next frequency measurements.

The computation of the frequency measurements does not depend on the duty cycle of the source reference signal. It depends on its frequency since the capture compare 1 interrupt is configured to occur on every rising edge of the reference signal (refer to *Figure 1*).

Figure 4 provides the frequency measurement algorithm.

Figure 4. RC frequency measurement flowchart


Enter TIM capture compare interrupt
Measurement done ?
Yes
No
Get TIM input capture
Compute current RC frequency
Add it up to the sum of frequencies
Counted periods = Number of periods defined
No
Yes
Compute the current frequency average
Initialize the number of overflows
Set MeasurementDone software flag
Increment the number of counted periods
Exit interrupt
Enter TIM update event interrupt
Measurement done ?
Yes
No
Increment the number of overflows
Exit interrupt
ai15845

3.2 `HSI_CalibrateMinError()` function

This function calibrates the HSI to have the nearest frequency to 8 000 000 Hz. It measures all 32 frequencies (32 values of the HSITRIM bits) and provides the HSITRIM value that corresponds to the frequency with the minimum error. The so-obtained HSITRIM value is the calibration value that is written to the HSITRIM bits in the RCC_CR register.
The frequency measurement starts from HSITRIM = 0 and ends with HSITRIM = 31.

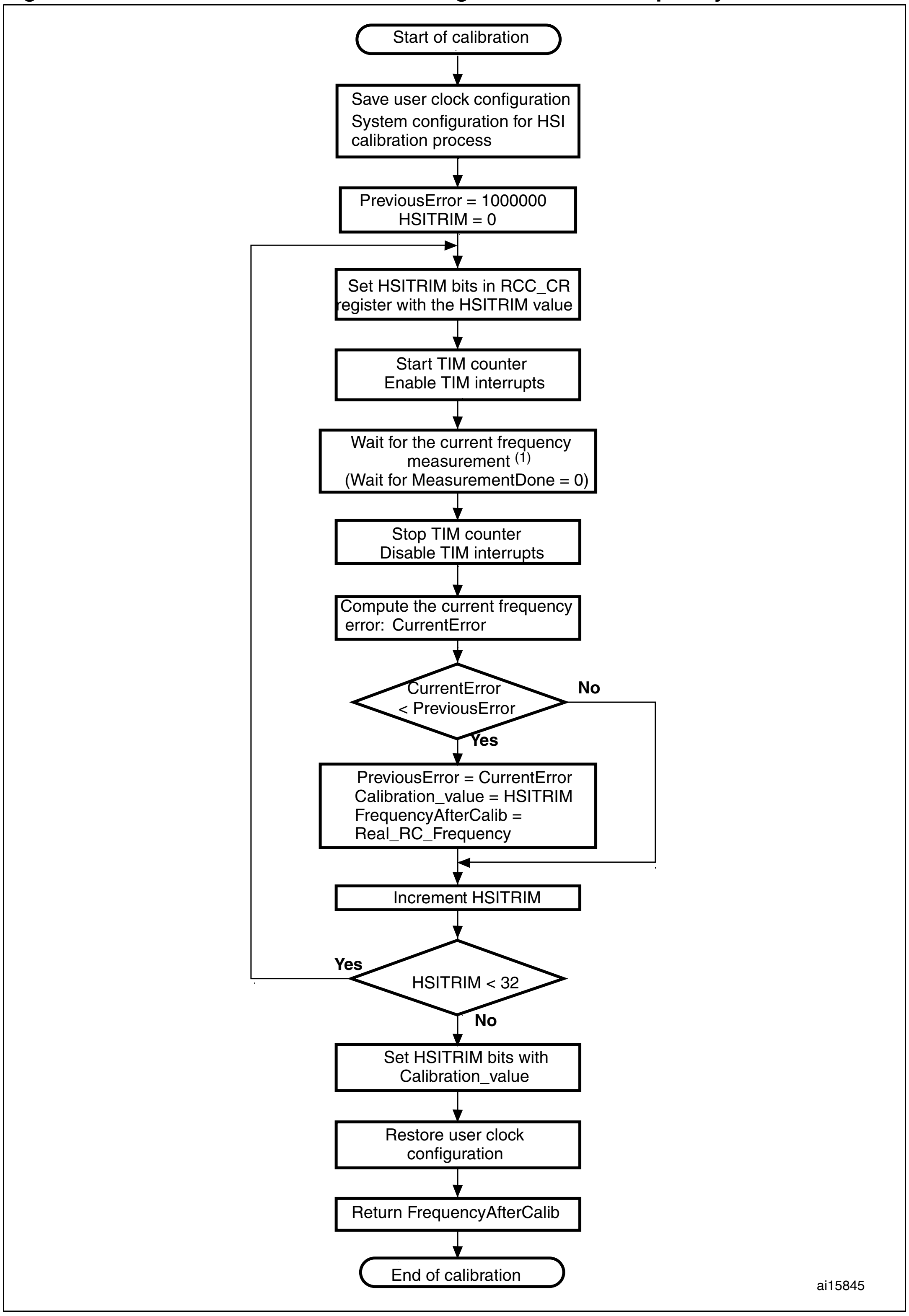
After calibration, the `HSI_CalibrateMinError()` function returns the RC frequency value as a signed 32-bit integer (s32). This value can be helpful to reconfigure prescalers, like the ones used for communication peripherals.

The flowchart in *Figure 5* gives the algorithm for this function.

Example

```
s32 FrequencyValue = 0;
int main()
{
......
/* Calibrate the internal RC with the frequency having the minimum
error found and return the RC frequency in Hz after calibration */
FrequencyValue = HSI_CalibrateMinError();
.........
}
```

Figure 5. RC calibration flowchart: finding the minimum frequency error


Start of calibration
Save user clock configuration
System configuration for HSI calibration process
PreviousError = 1000000
HSITRIM = 0
Set HSITRIM bits in RCC_CR register with the HSITRIM value
Start TIM counter
Enable TIM interrupts
Wait for the current frequency measurement (1)
(Wait for MeasurementDone = 0)
Stop TIM counter
Disable TIM interrupts
Compute the current frequency error: CurrentError
CurrentError < PreviousError
No
Yes
PreviousError = CurrentError
Calibration_value = HSITRIM
FrequencyAfterCalib = Real_RC_Frequency
Increment HSITRIM
Yes
HSITRIM < 32
No
Set HSITRIM bits with Calibration_value
Restore user clock configuration
Return FrequencyAfterCalib
End of calibration
ai15845

1. Refer to *Section 2.1* and *Section 3.1*.

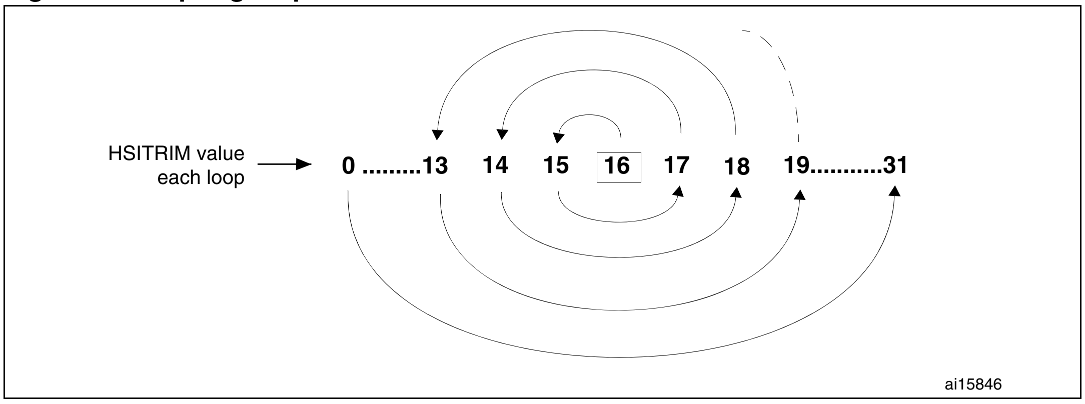
3.3 `HSI_CalibrateFixedError()` function

This function is provided to calibrate the internal RC with a maximum allowed frequency error. It is configured by the user as an absolute value given in hertz (the first parameter: *`AllowedErrorMax`*). This function is the same as `HSI_CalibrateMinError()` (refer to *Section 3.2*.), but it searches for the frequency that has an error (in absolute value) less than or equal to *`AllowedErrorMax`*.

- If it finds this frequency, it stops searching and configures the HSTRIM bits according to this frequency and returns SUCCESS, meaning that the calibration operation has succeeded.
- If not, it continues searching for it until the HSITRIM bits = 31 (32nd frequency). It then sets the HSITRIM bits to 16 (default value) and returns ERROR, meaning that the calibration has failed and did not find any frequency with an error less than or equal to *`AllowedErrorMax`*.
  The frequency measurements start with HSTRIM = 16 (unlike in the `HSI_CalibrateMinError()` function where frequency measurements start from 0 to end with 31). The HSITRIM value is computed in loops to find the next value. That is, the HSITRIM value starts from16 then goes to the next value to the left, then to the next to the right, then to the second to the left and so on until it reaches 31, forming a "spring loop" (as shown in *Figure 6*).

  This algorithm is based on the fact that the probability of finding the frequency that has the minimum error increases when the HSITRIM bit value tends to 16, and decreases when it tends to 0 or 31. This algorithm is implemented so as to minimize the time taken by the calibration process.

Figure 6. "Spring loop"



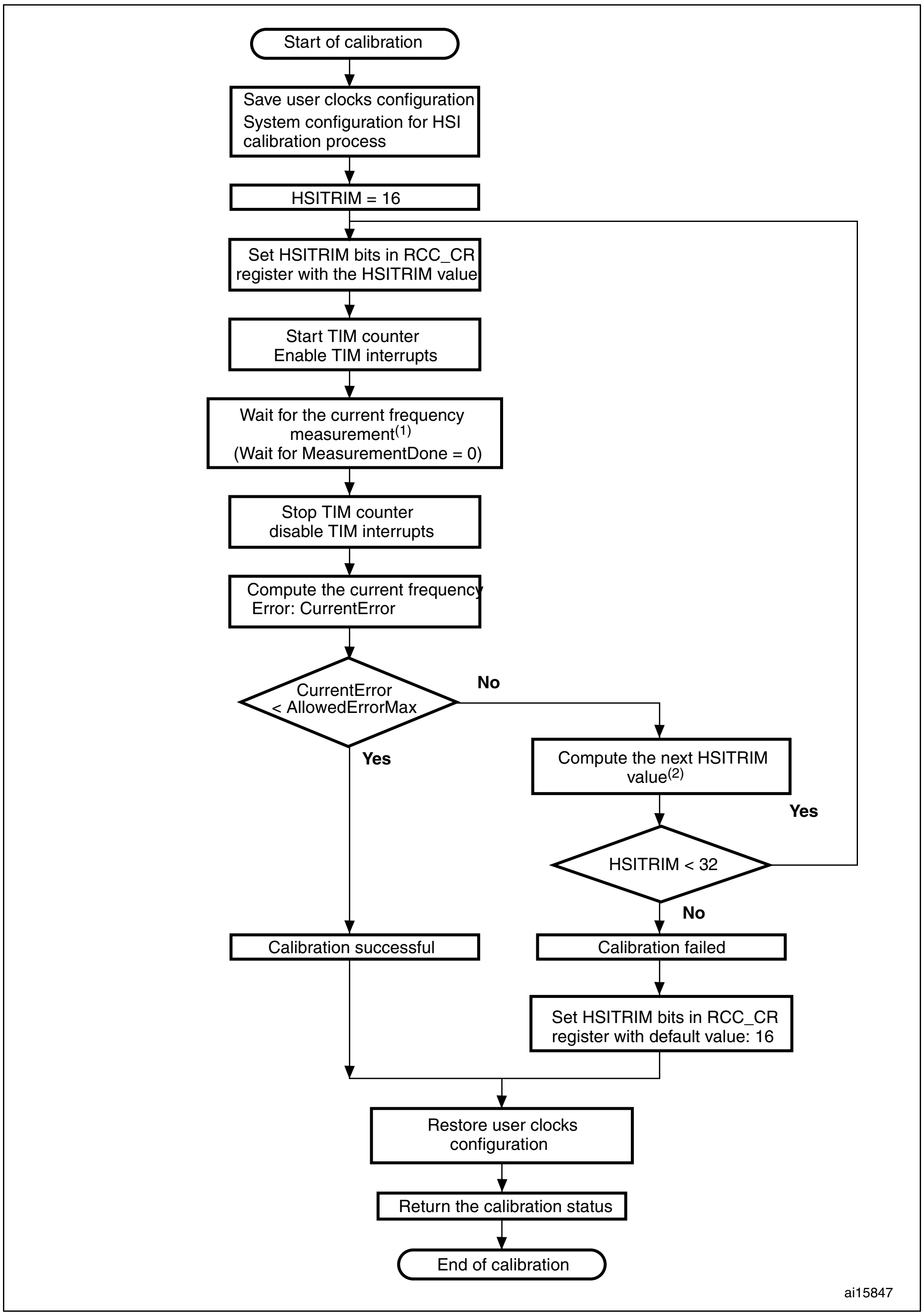
The second parameter is used to get the frequency (in hertz) after calibration in the form of a signed 32-bit integer (s32).

The flowchart in *Figure 7* gives the algorithm for this function.

Example

```
#define LED_Green
#define LED_Red
s32 FrequencyValue = 0;
ErrorStatus CalibStatus = ERROR;
int main()
{
......
/* The allowed frequency in absolute value is 14000Hz */
CalibStatus = HSI_CalibrateFixedError(14000, &FrequencyValue);
if(CalibStatus = SUCCESS)
{
GPIO_SetBits(GPIOC, LED_Green);
}
else
{
GPIO_SetBits(GPIOC, LED_Red);
}
......
}
```

Figure 7. RC calibration flowchart: calibration with the maximum allowed frequency error


Start of calibration
Save user clocks configuration System configuration for HSI calibration process
HSITRIM = 16
Set HSITRIM bits in RCC_CR register with the HSITRIM value
Start TIM counter Enable TIM interrupts
Wait for the current frequency measurement(1) (Wait for MeasurementDone = 0)
Stop TIM counter disable TIM interrupts
Compute the current frequency Error: CurrentError
CurrentError < AllowedErrorMax
No
Yes
Compute the next HSITRIM value(2)
Yes
HSITRIM < 32
No
Calibration successful
Calibration failed
Set HSITRIM bits in RCC_CR register with default value: 16
Restore user clocks configuration
Return the calibration status
End of calibration
ai15847

1. Refer to *Section 2.1*.
2. Refer to *Figure 6*.

3.4 Calibration demo description

The demo provided with this application note shows the ability of the firmware to calibrate the STM32F10xxx HSI.

A green and a red LED have to be connected to GPIO port C pins, the green LED to the PC5 pin and the red LED to PC6.

Five other LEDs have to be connected from PC0 to PC4 to show the value of the HSITRM bits in the RCC_CR register.

By default, the demo is configured for calibration of the HSI using the RTC/64 source frequency. Please, remember to connect PC13 to PA6 (as shown in *Section 2.2.1*) as the calibration process will wait until an available source signal is present on the PA6 pin.

By default, the number of measured periods per frequency is set to 10.

```
#define NbOfPeriod       10
```

To run the calibration process that provides the frequency with minimum error, you have to comment the following define in the *main.c* file. Conversely, to run the calibration process that finds the frequency with a maximum allowed error, you have to uncomment the same line:

```
//#define USE_HSI_Fixed_Error
```

To show the RC signal, connect an oscilloscope probe to the PA8 pin and uncomment the following line in the *main.c* file:

```
#define OUTPUT_RC_ON_MCO_FOR_DEBUG
```

When running the demo for calibration with minimum frequency error, you can visualize the frequency changes on the oscilloscope while the HSI frequency is being measured. You can also see the frequency stabilize after completion of the calibration process. The LEDs connected from PC0 to PC4 will light up according to the value of the HSITRIM bits in the RCC_CR register (binary value). The green LED will also light up.

When running the demo for calibration with maximum allowed error, you can visualize the frequency changes on the oscilloscope while the HSI frequency is being measured. You can also see the frequency stabilize after completion of the calibration process. If the calibration process has succeeded, the green LED lights up, otherwise (if calibration has failed) the red LED lights up. In both cases, the five LEDs (connected from PC0 to PC4) light up according to the value of the HSITRIM bits in the RCC_CR register after calibration.

3.5 Recommendations on the use of the HSI calibration library

1. The NVIC must be configured as described below for all TIM3 interrupts when the HSI calibration library is being used. This configuration is reserved for TIM3 interrupts:

   ```
   NVIC_InitStructure_IRQChannel = TIM3_IRQChannel;
   NVIC_InitStructure.NVIC_IRQChannelPreemptionPriority = 1;
   NVIC_InitStructure.NVIC_IRQChannelSubPriority = 1;
   ```

   Capture compare 1 and update event interrupts are also reserved for the calibration process.
2. Frequency measurement accuracy is not guaranteed when using a reference frequency that exceeds 3 kHz.
3. After calibration, the two calibration functions restore the user clock configuration since they have their own clock configuration. So, you should call your system clock configuration function as follows:

In the *HSI_calibration.c* file

- Declare the user clock configuration as external:

```
/* Private function prototypes ---------------*/
external void My_RCC_Configuration(void);
```

- Call the user configuration as follows:

```
void Restore_RCC_UserConfiguration(void)
{
/* Call your default RCC configuration here */
My_RCC_Configuration(void);
}
```

4. It is not recommended to call calibration functions in an interrupt routine since, in this case, the calibration process may be long (refer to the *Section 4.2*).
5. It is recommended to stop all application activities before the calibration process, and to restart them after calling the calibration functions. The application therefore has to stop communications, ADC measurements (see *Note: 1*) etc. since these processes are supposed to use clock configurations that are different from those used in the calibration process. Otherwise, errors might be introduced in the application: errors while reading/sending frames, ADC reading errors since the sampling time has changed, etc.

Note: 1 1) Except when using the ADC for the calibration process (refer to 7.).

6. If your application uses the RTC output source on the TAMPER-RTC pin, and selects a source different from RTC/64 (`BKP_RTCOutputSource_CalibClock`), its configuration will be lost and the pin will have to be reconfigured according to your application requirements.
7. Real-time calibration vs. temperature can be used when the ambient temperature changes noticeably while the application is running. The internal temperature sensor can be used with the ADC watchdog with two thresholds. Each time an ADC watchdog interrupt occurs, a new RC calibration process has to be performed and the two thresholds are updated according to the current temperature (this feature is not implemented in this application note):

   Threshold_High = CurrentTemperatureValue + TemperatureOffset

   Threshold_Low = CurrentTemperatureValue – TemperatureOffset

4 Calibration process performance

4.1 Accuracy of frequency measurements

The accuracy of HSI frequency measurements depends on the accuracy/stability of the reference frequency and on its value. Since the measurements also depend on the finite resolution of the timer, it is recommended to use a reference frequency that does not exceed 3000 Hz. Measurement accuracy is not guaranteed when the used frequency is higher than 3000 Hz.

Table 2 gives an idea of the efficiency of calibration versus reference frequency accuracy.

Table 2. RC frequency accuracy vs. reference frequency accuracy(1) (2)

Reference frequency accuracy	RC frequency accuracy (after calibration)
0% to 0.1%	0% to 0.2%
0.2% to 0.5%	0.3% to 0.6%
0.6% to 1%	0.7% to 1.1%
1.1% to 2%	1.2% to 3%

1. These accuracy values are indicative only and they give a rough idea of the RC frequency error ranges that can be obtained after calibration. The RC frequency error also depends on the chip.
2. These values remain true even if the HSI frequency is multiplied. This means that the use of a PLL does not multiply the frequency error of the system clock. The accuracy remains the same.

4.2 Duration of the calibration process

The duration of the calibration process depends on:

1. The used reference frequency
2. The number of measured periods per frequency (`Ref_Frequency` value defined in the *HSI_calibration.h* file)
3. The number of measured frequencies during the calibration process

The duration of the calibration process is given by:

$$\text{CalibDuration} = \left\langle \frac{(\text{NPeriod} + 1) \times \text{NFreq}}{F_{\text{ref}}} \right\rangle + \text{ErrorCompDur} + \text{ConfigRestoreDur}$$

Where:

– *NPeriod* is the number of times the frequency is measured in the same HSITRIM configuration (the same frequency)

– *NFreq* is the number of measured frequencies (number of HSITRIM values used for the frequency measurement)

– F_{ref} is the used reference frequency in Hz

– *ErrorCompDur* is the time the computation takes to calculate the frequency error. It takes around 14 µs.

– *ConfigResotreDur* is the time the calibration process takes to configure the system for HSI calibration and restore the user configuration after this process (that is RCC, TIM, NVIC, etc.). It takes around 280 µs.

Note: *In each measured frequency, the first period captured is not taken into account in order to measure a stabilized frequency. This is why 1 is added to NPeriod in the CalibDuration equation above.*

In the case of the calibration process with a minimum frequency error (`HSI_CalibrateMinError()`) the number of NFreq is equal to 32. If the RTC/64 is used as the reference frequency (512 Hz) and the selected number of measured periods configured by the user is 10, the calibration takes around 688 ms.

$$\left\langle \frac{(10+1)\times 32}{512} \right\rangle + 300\ \mu s\ =\ 688\ ms$$

In the case of the calibration process with a maximum allowed error (`HSI_CalibrateFixedError()`), NFreq changes from chip to chip. NFreq also depends on the maximum allowed error that is selected. The higher the selected allowed error, the more NFreq will tend to 1. The lower the selected allowed error, the more NFreq will tend to 32.
So, the duration of the calibration process with a maximum allowed error is lower than or equal to the duration of calibration when using the minimum frequency error process.

5 Conclusion

Several frequency sources can be used to calibrate the internal RC oscillator: the RTC crystal, the AC line (to use mains refer to the AN2326 application note), etc. Whatever the reference frequency source, the RC calibration principle is the same: a reference signal must be provided for measurement by a timer. The higher the accuracy of the reference signal frequency, the better the accuracy of the RC frequency measurement. The error is computed as the absolute value of the ideal RC frequency value and the measured one. From this, the calibration value is calculated and written to the HSITRIM bits in the RCC_CR register.

If you choose to use the RTC crystal as the reference frequency source, the maximum RC frequency error is 0.2%.

6 Revision history

Table 3. Document revision history

Date	Revision	Changes
02-Feb-2009	1	Initial release.