

FMCW Radar Sensors

APPLICATION NOTES

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Frequency Modulated Continuous Wave Radar

Basic operating principles and theory

FMCW (Frequency Modulated Continuous Wave radar differs from pulsed radar in that an electromagnetic signal is continuously transmitted. The frequency of this signal changes over time, generally in a sweep across a set bandwidth. The difference in frequency between the transmitted and received (reflected) signal is determined by mixing the two signals, producing a new signal which can be measured to determine distance or velocity. A sawtooth function is the simplest, and most often used, change in frequency pattern for the emitted signal.

FMCW radar differs from classical pulsed radar systems in that an RF signal is continuously output. Consequently, time of flight to a reflecting object can not be measured directly. Instead, the FMCW radar emits an RF signal that is usually swept linearly in frequency. The received signal is then mixed with the emitted signal and due to the delay caused by the time of flight for the reflected signal, there will be a frequency difference that can be detected as a signal in the low frequency range. A schematic presentation is shown in Figure 1.

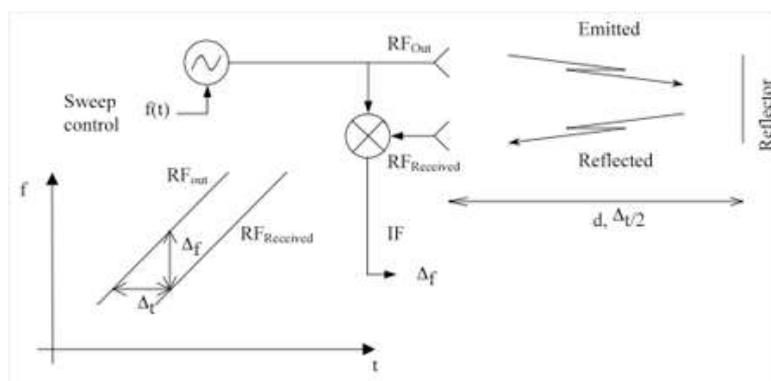


Figure 1. Schematic presentation showing how a low frequency signal is generated by mixing the received RF signal with the output RF signal. Due to the delay, Δt , caused by emitted signal

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traveling the distance to the reflector and back to the receiver, there will be a small difference in signal frequency between the two RF signals. This is output as an IF-signal with frequency Δf .

A simplified derivation of the intermediate frequency (IF) signal with the frequency Δf can be made in the following way: assume that the RF signal generator will output a frequency that is changing linearly over time as:

$$f_{RF\text{Out}} = f_{RF0} + k_f * t, 0 \leq t < T \quad \text{eq. 1}$$

where f_{RF0} is the starting frequency, T is the frequency sweep time and k_f is the slope of the frequency change, i.e. the sweep rate:

$$k_f = \frac{BW}{T} \quad \text{eq. 2}$$

where BW is the frequency sweep bandwidth. The delay caused by the round-trip of the emitted signal to the reflector is calculated as:

$$\Delta t = 2 \frac{d}{c} \quad \text{eq. 3}$$

where d is the distance between the radar antenna and the reflector and c is the speed of light. Due to the delay, the frequency of the received signal compared with the emitted signal will be:

$$f_{RF\text{Received}} = f_{RF0} + k_f * (t - \Delta t), \Delta t \leq t < T + \Delta t \quad \text{eq. 4}$$

The difference in frequency, Δf , between $f_{RF\text{Received}}$ and f_{RF0} is thus:

$$\Delta f = k_f * (-\Delta t) \quad \text{eq. 5}$$

This is the signal that is output from the detector. The minus sign can be omitted since the real signal frequency output from the radar detector is wrapped to a positive frequency. Thus the expression can be written as:

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$$\Delta f = \frac{BW}{T} \cdot 2 \frac{d}{c},$$

eq. 6

Typical values for the RS3400 series modules would be a frequency sweep, BW, of 1500 MHz over T=75 ms corresponding to a sweep rate, k_f , of 20 000 MHz/s. A distance, d, between the radar and a reflector of 15 m would give a delay, Δt , of 0.1 μ s and the IF signal frequency, Δf , would then be 2000 Hz. This signal is easily sampled with a high resolution ADC in order to be detected. If several reflectors are appearing in the measurement setup, the resulting IF signal will contain superpositions of the individual IF-signals from the echoes.

Different echoes are distinguished by their unique IF signal frequency and a Fourier transform of the sampled signal can be used to extract the distances to the different targets. The measurement range of the system is limited by the sensitivity of the detector and the sampling rate of the ADC. For the RS3400 series a sampling rate of 20 kHz gives a maximum detectable IF signal frequency of 10 kHz, which corresponds to a range of 75 m. Longer ranges are easily achievable by either increasing the sample rate or lowering the sweep rate. In addition, antenna gain needs to be fairly high in order to provide sufficient signal levels for the detector.

Theoretical performance

The fundamental range measurement resolution of the system can be estimated as follows. The Fourier transform of a time limited signal can only detect an IF signal frequency with a resolution of $1/T$, keeping in mind that $\Delta t \ll 1/T$; thus the sampling time can be approximated by T. Using equation 6, this gives the minimum change in d, Δd , as:

$$\frac{1}{T} = \frac{BW}{T} \cdot 2 \frac{\Delta d}{c},$$

eq. 7

which can be transformed to:

$$\Delta d = \frac{c}{2BW},$$

eq. 8

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showing that the range measurement resolution is only limited by the sweep bandwidth. This is an important observation since it says that resolution is not dependent on the frequency of the RF signal itself, but rather only on the sweep bandwidth. There are methods of increasing the resolution of the measurements by a factor of 10 to 100 using fitting algorithms. These find a peak in the IF signal spectrum which is not at an integer frequency point defined by the sampling rate and sweep bandwidth.

The range detection and FMCW radar principle may also be derived using a characterization of the IF signal phase rather than the frequency. This is recommended in order to understand the possibilities of a discrete system where the frequency sweep really is generated by a discrete set of frequencies. This derivation also lends itself more directly to high resolution range measurements. For the simplicity of understanding the measurement principle it is however unnecessary and is thus included as an appendix.

Detailed operating principles and theory

FMCW radar principles using phase measurement (time discrete version).

FMCW radar functions by outputting a continuous RF signal, whose frequency is swept over a specific frequency band. Synthesized modules, like RS3400, are in fact not sweeping the frequency continuously, but rather step the frequency with a set of discrete frequency points. Thus, these systems are also called Stepped Frequency Continuous Wave (SFCW) radar. The synthesized signal source assures very precise frequency control, which is important for the accuracy and repeatability of measurements.

The RF signal will be radiated and reflected against different objects. The echo is then received and compared (mixed) with the radiated RF signal. Had the system been measuring time-of-flight for a pulsed signal, the sensor output could be linear with distance. In an FMCW, however, the sensor output corresponds to the cosine of the phase difference between the echo signal and the radiated signal.

$$s = \cos(\Phi)$$

eq. 9

where s is the output signal from the sensor and Φ denotes the phase difference between the echo RF signal and the radiated signal.

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In other words, the measurement signal from the sensor will be a cosine signal indicating the round-trip electrical distance which the radiated signal has traveled.

$$s = \cos\left(2\pi \frac{2d}{\lambda}\right) \quad \text{eq. 10}$$

or

$$\Phi = 2\pi \frac{2d}{\lambda} \quad \text{eq. 11}$$

where d is the distance to the reflecting object and λ is the electrical wavelength of the RF signal. The multiplication by 2 accounts for the round-trip.

The expression for Φ can also be written as

$$\Phi(f_{RF}) = 2\pi \frac{2d}{c} f_{RF} \quad \text{eq. 12}$$

where λ has been substituted with, c , the speed of light and f_{RF} is the frequency of the RF signal.

For any measurement (except for those at very short distances) the electrical distance will exceed one wavelength and there will be ambiguities about the measurement result. Fortunately, the RF signal can be stepped in frequency and several measurements can be performed. From eq. 12, it is clear that Φ will increase linearly with f_{RF} and thus the detector output will be a cosine shaped signal. A small value of d , meaning a close echo, will create a slowly varying detector signal and a distant echo will create a quickly varying detector signal. The frequency of the RF output signal, f_{RF} , is stepped over the available band (BW). For the RS3400S, this band is from 4625 MHz to 5375 MHz, with BW = 750 MHz. For the RS3400X, this band is from 9250 MHz to 10750 MHz and for the RS3400K this band is from 24000 MHz to 25500 MHz, i.e., BW = 1500 MHz. The expression for Φ is then:

$$\Phi(n) = 2\pi \frac{2d}{c} \left(f_{RF_0} + \frac{n}{N} BW \right) \quad \text{eq. 13}$$

where n indicates each unique measurement, $n = 0, 1, \dots, \text{and } (N-1)$ and N is the number of frequency points used for the measurement sequence. The term f_{RF_0} denotes the starting frequency. Recalling that the detector output is the cosine of Φ , the equation will be as follows:

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$$s(n) = \cos\left(2\pi \frac{2d}{c} \left(f_{RF_0} + \frac{n}{N} BW\right)\right) \quad \text{eq. 14}$$

Since the cosine function only is unique over the range $[0, \pi]$, the expression can be simplified to:

$$s(n) = \cos\left(\Phi_0 + 2\pi \frac{2d}{c} \frac{n}{N} BW\right) \quad \text{eq. 15}$$

where Φ_0 accounts for the phase value at the starting RF signal frequency of the sweep. It should be noted that Φ_0 can be limited between 0 and π . To extract the value of the distance to the reflector, d , one needs to estimate how much Φ changes over the frequency sweep. One simple way is to take the Fourier transform of the signal $s(n)$.

$$S(m) = \text{fft}(s(n)) \quad \text{eq. 16}$$

Here m denotes the normalized index in the transformed domain, $m=0, 1, \dots, (N-1)$.

With the detector signal being a time varying signal, m can be seen as the index in the frequency domain for the detector signal. As an alternative, this domain may be seen as a distance domain. For simplicity, this domain will be called frequency domain or spectrum in this text since in most cases it is the typical interpretation of a Fourier transformed signal.

Recalling that the Fourier transform of a cosine yields two Dirac-delta functions, the transform of $s(n)$ becomes:

$$S(m) = \frac{1}{2} \left(\delta\left(m - \frac{2d * BW}{c}\right) + \delta\left(m + \frac{2d * BW}{c}\right) \right) \quad \text{eq. 17}$$

The second term on the right hand side refers to a peak at a negative value of m , this can be easily converted to a positive value by adding N , but is of no further interest here. The first term on the

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right hand side will have a peak at $m=(2d*BW/c)$. Conversely, if a peak is identified at $m=m_0$, the corresponding distance to the reflector can be calculated as:

$$d = m_0 \frac{c}{2BW} \quad \text{eq. 18}$$

Thus, a ranging function is achieved.

It is worth noticing that eq. 18 is completely independent of the center frequency of the RF signal. In fact, to get an impression of the resolution that is available from only extracting a measurement of the distance based on the maximum peak found in the frequency domain, the difference between two integer values of m is $c/2BW$. This shows that the resolution is only depending on the sweep bandwidth of the RF signal and not of its specific frequency. A frequency sweep from 9250 to 10750 MHz will give the same resolution as a frequency sweep from 24000 to 25500MHz.

For the specified frequency sweep with $BW = 1500M$ Hz, the integer range measurement resolution will be 0.10 m.

In order to achieve higher resolution in range measurements, a weighted average of several frequency points can be used to find a peak location that is positioned between integer points in the spectrum. Additionally, when a single echo is available in a local part of the spectrum, it is possible to estimate d based on the slope of the phase angle Φ . Using only the first term in the right hand side of eq. 17, recall that the inverse Fourier transform of a Dirac-delta function is a complex exponential:

$$\text{ifft}\left(\delta\left(m - \frac{2d * BW}{c}\right)\right) = e^{-j2\pi \frac{2d * BW}{c} N} \quad \text{eq. 19}$$

Here, the right hand side is a complex series of N points. In a real-life measurement, the signal will not be an ideal complex exponential like in eq. 19. However, an inverse Fourier transform of only a section of the spectrum around a peak of interest will give a complex signal whose phase angle may be extracted. Using this phase angle, the slope may, for example, be found using a least squares fit to a linear expression.

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Applications

FMCW radars in the GHz spectrum provide excellent distance measurement performance in applications where high accuracy, repeatability and reliability are needed. Because of the short wavelength (12 mm for a 24 GHz signal), resolutions on the order of 2 cm can be achieved over distances of 20-30 meters. This allows FMCW sensors to excel in applications such as tank level gauging where high resolution non-contact measurements are needed.

FMCW sensors have been used in oil and LNG tankers and storage tanks to measure product volumes, in commercial, military, and unmanned aircraft as altimeters, and in industrial applications for the verification of product dimensions in automated systems.

Due to the non-contact nature of the measurement system, and due to the nature of the microwave, FMCW radar operating in the GHz range also exhibit excellent resistance to dust, steam, heat, etc. This allows for use in conditions as demanding as those found in the blast furnace of a steel mill.

Due to their ability to determine range over very short or fixed distances, FMCW based systems have also been in transportation applications, including automotive collision avoidance radars and marine radars. Other applications have included wall-penetrating radar for imaging and detection, security sensors against intrusion, and human vital-sign detection and measurement. In summary, radar sensors using FMCW principles perform extremely well in situations requiring non-contact measurement of distance in harsh conditions.

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Competing technologies

Infrared

Advantages: Good at detecting orthogonal and tangential movement, with wide field of view and low cost

Disadvantages: Poor at detecting radial movement, can have difficulty in diminished visibility conditions such as rain or dust, can not be used to detect range, direction, or speed of objects. Requires a high-quality transparent window for the sensor, making the system more difficult to conceal. The sensor can also be affected by dirt or moisture on the window or in the atmosphere.

Ultrasound

Advantages: Relatively accurate at short ranges, triangulation possible, low cost

Disadvantages: Tends to have a very low range. Provides no velocity information. Requires a visible sensor. Can be influenced by environmental factors such as noise, wind and temperature

Radar (pulsed)

Advantages: Proven technology with long history. Long detection ranges possible using high power systems. Can be designed to deal with nearby reflectors and interference relatively easily.

Disadvantages: High peak power output and radiation. Has difficulty with measurements at short ranges due to short signal travel time. More difficult to eliminate clutter. Can take time to “warm up”.

Laser

Advantages: Highly directional. Quick start up and measurement. Excellent for range finding. More difficult to detect or jam. Relatively low cost.

Disadvantages: Can be affected by atmospheric conditions including fog, rain and temperature. Does not work well on all surfaces. Limited field of view can prevent detection of multiple targets.

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Cameras/Video

Advantages: Highly flexible, can be programmed to recognize different objects, not just range and velocity. Sensors can be low cost.

Disadvantages: Requires clear field of view, can be affected by shadows or bad weather, etc...
Requires complicated software and powerful hardware

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Advantages and disadvantages of FMCW radar

Advantages

High resolution distance measurement

Mm-wave FMCW radars can have very high resolution for ranging, velocity and imaging application. A distance measurement resolution of 2 cm can be easily achieved over 20-30 meters. Accuracy for non-moving targets is better than for moving targets, and requires less processing power. Measurements of moving targets are of course possible, but requires more powerful algorithms and hardware. Other technologies such as infrared or ultrasonics cannot detect range or only over very limited distances.

Quick updating of measurement

Because FMCW mm-wave radars are continuously transmitting a signal, there is little delay in measurement updates, as can be the case with pulsed systems. Additionally, solid state electronics produce almost instantaneous start up times, as compared to pulsed systems often using magnetrons. Systems based on lasers, ultrasonics, or infrared will have similar update speeds to FMCW systems.

Functions well in many types of weather and atmospheric conditions

Due to the short wavelength of the electromagnetic radiation used, mm-wave systems have excellent performance in rain, humidity, fog and dusty conditions. The short wave-length means that raindrops, water vapor or dust particles do not block wave propagation easily. Heavy rain is generally required before a reduction in range or resolution occurs. mm-wave systems will function identically during day or night. FMCW radars are also immune to effects from temperature differences, or high temperatures.

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Better electrical and radiation safety

Sivers IMA modules are designed to be inherently safe, for use in an explosive atmosphere such as an oil tanker or LNG storage facility. They are completely sealed and tested, so there is no risk of sparking, resulting in fire or explosion.

Compared to pulsed radar systems, the peak emitted electromagnetic radiation is far lower in a FMCW radar system. This is important in applications where people are close to the antenna, as the peak emitted energy is far lower. This allows for more flexibility in selecting a mounting location for the antenna. The lower peak power requirements also allow for lower power consumption in the supporting electronics, resulting in lower costs and technology needs.

Infrared and video based systems are passive systems, and therefore do not emit a signal for measurement purposes. Most laser based ranging systems use low power emitters, and are considered eye-safe.

Good range compared to other non-radio technologies

Compared to systems operating in the visible or infrared light spectrum, or those using ultrasonic waves, FMCW radar sensors have excellent measurement range due to superior signal propagation.

Can be mounted invisibly (behind radome)

FMCW mm-wave radar systems can be mounted behind a wide variety of radio-transparent materials including most plastics and fiberglass. This allows for use in applications where the sensor must be concealed for security, weather resistance or aesthetic reasons.

Can penetrate variety of materials

Mm-waves are capable of penetrating a variety of non-metallic materials. These can include wood, concrete, various polymers and composites. This allows mm-wave based systems to be easily concealed, or to be used for measurement or detection of concealed or covered targets. All other non-microwave based systems require an exposed sensor or window to function, and can not penetrate a majority of materials.

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Better at detecting tangential motion than Doppler based systems

Since FMCW based systems do not require movement towards or away from the antenna to detect range, an 2D or 3D FMCW based system will be better at detecting tangential or orthogonal movement compared to Doppler-pulse systems when used in a scanning capacity.

Infrared and video based systems are also excellent at detecting movement, but may not be able to quantify the direction or magnitude of the movement.

Disadvantages

Reduced range compared to pulse radar

Due to the generally lower peak power output of FMCW radar systems, their long range performance can be lower than compared to pulsed systems. Since the transmitted signal is not as strong the received signal will be attenuated by atmospheric effects, interference, and distance. FMCW radars are however competitive or superior to other competing technologies in range.

More expensive than competing technologies

Similar economies of scale have not been achieved in FMCW systems compared to pulsed and Doppler radar systems, due to the maturity of the existing technologies in the marketplace. Sivers IMA FMCW radar modules are however price competitive, and can be produced in large, commodity-scale volumes. Additionally, the module uses a standard 3-wire interface for control functions, allowing for easier integration, and less expensive R&D. Compared to infrared and ultrasonic systems, FMCW systems will generally be far more expensive.

Susceptible to interference from other radio devices

Because they are continuously transmitting across a frequency band, FMCW systems may be more susceptible to interference from other electronic systems. This is due to the larger range of frequencies encountered and due to the lower "peak" power, resulting in the returned signal being overwhelmed by other emissions. Pulsed systems can generally overcome interference by increasing transmitted power or by switching frequencies. Distance measurement or detection systems using infrared, video, or lasers are generally immune to interference, given their operating principles.

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Can be jammed

When use in defense applications, FMCW radars can be at a disadvantage compared to pulsed systems. Due to the lower power and continuous transmissions of FMCW systems, they may be more easily jammed by electronic warfare systems. Pulsed systems have an advantage in this regard in that their transmissions are intermittent in nature, their transmission frequency can be varied, and their power output is generally higher.

Not passive

FMCW radar systems continuously transmit, meaning that they are easily detected by electronic warfare systems. Pulsed systems may be more difficult to detect as they are not continuously transmitting. This would make the location of an FMCW easier using detection and triangulation techniques. Additionally, pulsed systems may also more easily be adapted to operate as passive detectors of other transmitters. Their non-passive nature and use of microwaves also means that they are be subject to regulations regarding radio interference and licensing.

Can require more computing power than pulse-Doppler systems

FMCW radar systems, given the need for high-quality fast Fourier transform processing to achieve accurate measurements, can require more advanced and powerful hardware. Given the continued decrease in computing cost, this is becoming less of an issue. However the development and programming required can also be more complex, increasing costs.

May be subject to licensing and regulations

Because they are radio transceivers, these sensors may be subject to regulations regarding interference. As larger bandwidth increases the resolution of an FMCW system, restrictions of frequency use may impact the possible measurement resolution. Non-radio technologies generally avoid this regulatory or licensing requirement.

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Licensing and regulation

Sivers IMA FMCW radar modules are designed to be used in high-performance, high bandwidth sensor systems. One consequence of this large available bandwidth is that the spectrum used in a frequency sweep may overlap with an existing licensed band. These other bands may be used in applications including military radar, satellite and terrestrial communications, and radio-astronomy. Licensing of the frequencies usable by RS3400 series radar modules varies widely around the world. Primary subjects to investigate in regard to local licensing and regulation when designing a system using these modules include the frequency band to be used, the intended power output, the application, and the location of use.

5 GHz

The RS3400S/00 sensor module cover frequencies from 4625 MHz to 5375 MHz, for a total bandwidth of 750 MHz. It is important to check local regulations as to the availability of usable frequencies, especially for outdoor applications. Indoor or enclosed applications generally have lower requirements, and may allow for more flexible usage. In the United States and Europe, this spectrum is set aside mainly for fixed wireless and radio-location and navigation services. This spectrum falls outside of the ISM license free band, but is sometimes used for unlicensed WiFi applications.

10 GHz

The RS3400X/00 sensor module can operate at frequencies from 9250 MHz to 10750 MHz, providing 1500 MHz of bandwidth. This spectrum is generally used for radio-location, fixed radio, and satellite communications systems in Europe and the United States.

24 GHz

The RS3400K/00 operates in the frequency band from 24000 MHz to 25500 MHz which is primarily used for telecommunication and industrial, scientific and medical (ISM) applications. One important use of this ISM band (which ranges from 24.00 to 24.25 GHz) is in automotive radar for collision avoidance. This application will however be phased out in 2013, in order to free up this spectrum for radio-astronomy usage. This change in frequency allocation should be considered if a system for outdoor usage is being developed.

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Relevant regulations (list not exhaustive)

Europe

EN 55011 – European emissions standards for ISM devices

EN 55022 – European emissions standards for ITE devices

EN 61326 – European standards on laboratory, testing and measurement equipment

CISPR 11 and 25

United States

FCC Part 15 - General regulations, cover communications device, radio emissions sources, etc..

FCC Part 18 – Covers industrial scientific and medical applications

FCC Part 90 – Covers commercial applications including radio-location systems

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Technical notes

Operating conditions

Sivers IMA FMCW radar sensors have been tested to perform in temperatures ranging from -10 to +70C. They can be stored in temperature ranging from -50 to +10C, and can resist a shock of 100g over 6 ms (MIL-STD-202G method 213B).

All models are fully sealed and are therefore ideally suited to operation in flammable or explosive atmospheres. Every unit is factory tested and guaranteed to be air-tight.

ESD considerations

In order to ensure consistent and optimum performance, please observe all normal electro-static discharge considerations when handling Sivers IMA FMCW modules, especially before they have been installed in the final application.

1. Avoid carpets, especially in cool dry areas.
2. Wear ESD preventive clothing, including wrist straps and foot wear
3. Use antistatic floor mats and work surfaces
4. Hold the module by its edges and avoid touching the contacts before installation

Power supply / biasing

The FMCW module requires approximately 400mW of power. This is applied at 10V 1mA, 4V 60mA and 3.3V 40mA. There is no specific order in which the bias should be applied. Bias voltage should however not exceed nominal values by more than 5%. All pins not specifically labeled should not be grounded.

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Physical connections

The RS3400 series of FMCW radar modules has two basic types of interface connections. Power supply, synthesizer control, and IF output is achieved through two rows of pins formed by Samtec interconnect strips (BBL-121-G-E), which interface with Samtec SL-series or compatible socket strips. The majority of pins are dedicated to power supply, ranging from +3.3 to +10 V and 1 to 80 mA. Care should be taken to only apply vertical force when inserting or removing the module from its interface in order to prevent bent or broken pins.

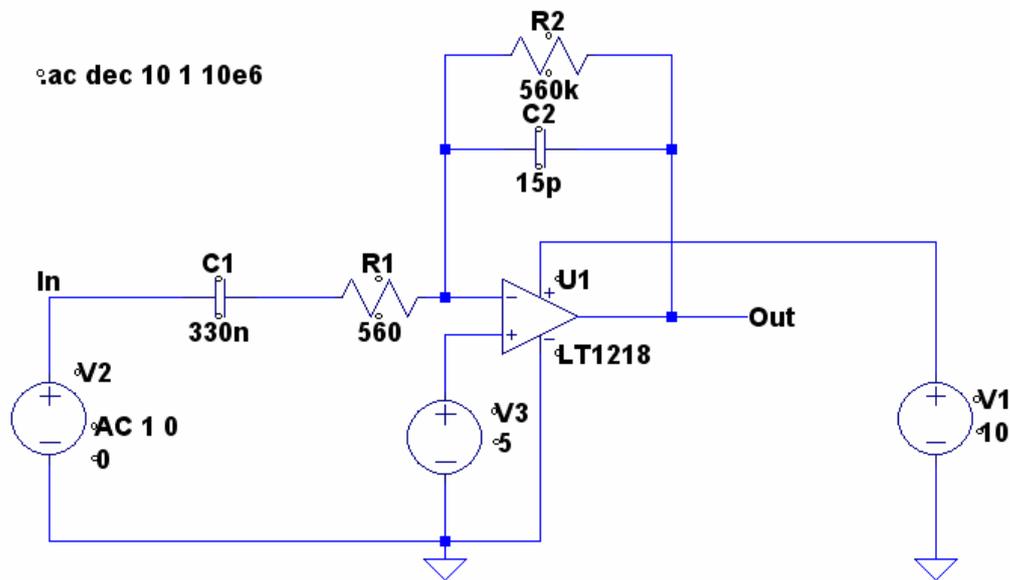
The antenna connection takes place using an SMA female connector. Care should be taken when connecting a coaxial cable or adapter. It is extremely important to use two wrenches in the attachment of the cable. One is used on the wrench flats found on the female SMA connector on the module to counteract the torque of the tightening operation. The other is applied to the locking nut on the cable. Ideally this will be a torque wrench, to help ensure proper attachment force for the cable, and to prevent damage to the interface and ensure the best connection. The recommended tightening torque is 0.3 – 0.6 N-m. An alternative method for connecting an antenna is to use a male-to-male SMA adapter. This provides a more direct, and therefore higher quality signal. Additional care must be taken in this case to avoid bending or damaging the SMA connector when handling the assembled system, due to the additional leverage provided by the antenna.

IF output signal characteristics

The output from the FMCW module is an IF-signal. No additional termination is necessary. The maximum signal level is approximately 500mVpp. Typical measurements may contain signal components with this magnitude due to inadvertent reflections in the system, but it is unlikely. The usual signal that is to be identified is however substantially smaller, typically in the single mV range or smaller. Based on the nature of FMCW systems, close reflections with a high magnitude will have a lower IF signal frequency than more distant reflections that usually are to be identified. This means that it is useful to high pass filter the IF signal in order to suppress the close echoes. A simple OP-AMP design with an added gain is shown below. This circuit provides 60dB gain at approximately 600Hz and rolls off both below and above. This ensures that echoes from close objects (low frequency) and high frequency noise is suppressed. The corner frequency will vary with applications. The current setup is useful for a 1500MHz sweep with a step size of 1MHz and 50 μ s dwell time at each frequency point. The IF signal should be sampled at the end of the dwell time, allowing for the system to settle completely.

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Antennas

The choice of antenna will be highly dependent on the intended application and the transmission medium one is working in. Additionally the antenna choice will have a large impact on the range and field of view of the final sensing system.

In outdoor applications a horn or patch antenna is generally most appropriate. For enclosed or indoor applications such as storage tanks or silos, horn antennas are common; other options may include wave-stick and wave-guide antennas, which provide better performance with certain storage vessel configurations. Installing the antenna or sensor into an existing still-well that was previously used for another measurement system may also be an option but may require more careful antenna selection.

Attention should especially be paid to the dielectric constant of the medium the antenna is interfacing with. For many applications the transmission medium will be air. However, given the inherently-safe nature of the design, use in other mediums, such as liquified natural gas or other explosive environments is also quite suitable.

Beamwidth

The beamwidth of the antenna will primarily determine the “field of view” of the sensor. A more narrow beamwidth will result in a more directional sensor. This can have advantages or disadvantage. If the beamwidth is too narrow, the intended target may be missed. If it is too wide, clutter may become a problem while trying to take measurements.

Gain

Beamwidth and gain are closely related. A higher gain antenna will generally have a narrower beamwidth and vice-versa. Higher gain generally results in longer range, at the cost beamwidth. Higher gain horn antennas are also generally larger in physical size. If this is a concern a patch antenna may provide a more compact alternative, however at significantly higher cost.

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Bandwidth

Given the wide bandwidth available in RS3400 series modules an appropriately high performance antenna with matching bandwidth should be selected to ensure high measurement resolution.

Location / connections

Another factor to take into account is the intended mounting configuration. The antenna can be located remotely from the FMCW sensor module requiring a connecting coaxial cable. This allows for more flexibility in system packaging or permits accommodation of adverse environmental conditions. There will however be an increase in losses and reflections due to this longer connection. Direct connection from the sensor module to the antenna is also possible, greatly reducing these effects. In extreme locations, such as in a steel mill or chemical plant remote location of the antenna due to temperature or corrosive effects may be an absolute requirement. The possibility of using waveguides instead of cabling also exists in these situations, providing a physically robust connection.

Many of our customers have used standard gain horn antennas in the evaluation FMCW measurement systems. A 20 dB antenna provides a good starting point for evaluation purposes, with a good balance between coverage and range. Based on results using this antenna, a more appropriate antenna may then be identified.

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Evaluation board user guide

Sensor module / evaluation board assembly

The evaluation system is delivered with the RS3400 series module mounted on the control board as shown in Figure 2. Power is delivered through the 2.5/5.5mm DC connector. Positive voltage, 10-12V, should be applied on the center pin. The control board is protected against reverse voltage. In order to prevent undesired noise, a linear power supply is recommended, but for simple tests, a switched supply should suffice. Communication between the PC and the control board is over a RS232 serial connection. Connect a straight serial line between the female DSUB9 of the control board and the PC. If the PC does not have an RS232 interface, easily installed USB to RS232 adapters are available in most computer stores.

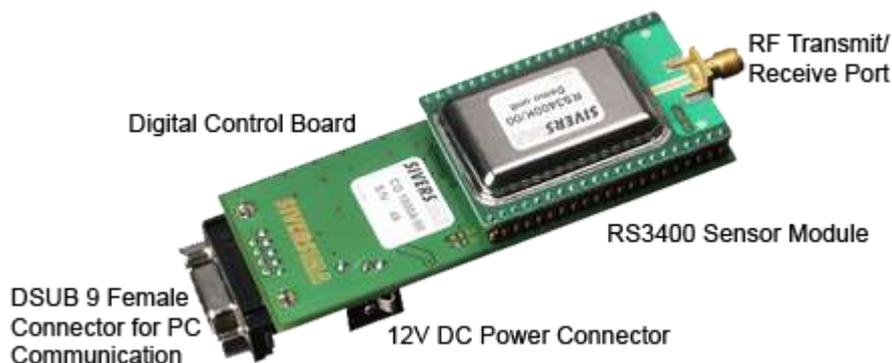


Figure 2. Controller board and radar sensor

In order to communicate with the evaluation board, a terminal emulation program is required. On older Windows systems (XP and older) Hyper Terminal works well. A free-open source alternative which has been found to also work is PuTTY, which is available online. To test the communication with the system, start a terminal window on the PC and configure the communications port where the control board is connected to the PC. The port can usually be identified using Windows device manager, select "Ports (COM & LPT)". Native ports are generally labeled COM1, COM2, COM3 or COM4. For USB-adapters, the COM-number is usually somewhat higher.

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The configuration of the port should be as follows:

- Bits per second: 115200
- Data bits: 8
- Parity: None
- Stop bits: 1
- Flow control: None

You may also want to turn on local echo in order to display your input in the terminal. Depending on the terminal emulator you are using, you may also want to enable session logging for retrieving measurement data from the text log file.

Make sure that the terminal program is started, the port configured correctly and the control board is connected to the serial line. Connect power to the control board. A green LED on the control board should light up. If the communication is working, a message should be displayed looking similar to the following:

```
SiversIMA AB
```

```
FMCW Eval board initialized
```

```
Software version: B RS3400
```

If the message is not displayed, try pressing the RETURN or ENTER key a few times. The character “?” should be displayed. If this is not the case, see the troubleshooting guide at the end of this section. With communication established between the computer and the control board, control of the RS3400 is now possible and measurements can be performed.

Now that communication with the evaluation board has been established, some type of waveguide will need to be attached. This is typically an antenna, but may be another device depending on the application. For ranging purposes, a 15-20dB standard gain horn is recommended. Bearing in mind that the possible sweep bandwidth is up to 750 or 1500 MHz, the antenna needs to have a fairly large bandwidth. It is very important that the antenna is connected using high quality cabling. It must be capable of operating at the frequency of the chosen module; otherwise high reflections and attenuation will occur, impeding the quality of the measurements.

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Trouble shooting guide for communication between the control board and a PC

Symptom	Possible Cause	Solution
The LED of the control board is not lit	Power is not supplied to the control board.	Connect 10-12V on the center pin of the 2.5/5.5mm DC connector
The terminal program or the control board is not responding when the enter key is pressed	The serial cable between the PC and the control board is not properly connected	Check serial cable connection
	The terminal program has not connected to the remote system.	Initiate communication within the terminal. For Hyper terminal, select menu Call and click on Call (alt+C, C) From within the terminal program, verify that the correct communications port is selected and that it is configured as described above.
	The communications port is not configured correctly	Try shifting the lines going to the DSUB9 connector pin 2 and 3. Change board to correct configuration by issuing respective command in PuTTY:
Controller board appears to be working correctly, but measurements are incorrect	Incorrectly configured controller board	HARDware:SYSTem RS3400S
		HARDware:SYSTem RS3400X
		HARDware:SYSTem RS3400K

FMCW Radar Sensors

Example FMCW radar measurement using the CO1000A/00 evaluation board

The following shows a typical measurement sequence and some trivial data manipulation in order to retrieve a distance measurement.

You will need the following items:

- ✦ RS3400 series sensor module
- ✦ CO100A evaluation board
- ✦ 12V power supply
- ✦ Serial cable
- ✦ USB adapter (if needed)
- ✦ Horn antenna
- ✦ RF cable or male to male SMA adapter (Note that for the RS3400K/00 operating at 24 GHz, higher quality connectors capable of operating at this frequency are required to ensure proper operation)
- ✦ Radar target (piece of sheet metal works well)
- ✦ Mathematical analysis software capable of fast Fourier transforms

The unit is connected to a standard gain horn antenna using a one meter RF cable. A metal sheet, used as a radar reflector, is positioned at approximately zero, one and two meters away from the horn opening during the three measurements.

Starting the units shows:

SiversIMA AB

FMCW Eval board initialized

Software version: B RS3400

Start by initiating the equipment. Setup the measurement, using defaults for most parameters. Position the radar reflector close to the horn antenna. Send the following commands to initialize the system, enable measurement and set the number of frequency sweeps to one:

```
INIT
```

```
SWEEP : MEASURE ON
```

```
SWEEP : NUMBERS 1
```

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Initiate a measurement sweep:

```
TRIG:ARM
```

Measurement completes in approximately 85 ms and data can be retrieved by typing:

```
TRACE:DATA ?
```

Depending on what terminal emulator you are using you may need to save the data at this point. If you are using Hyper Terminal, use the capture text command to save all 1501 measurements to a text file named S0.TXT. If you are using a terminal emulator such as PuTTY with session logging verify that your data has been captured by opening the log file. You can extract the data following all measurements.

Position the radar reflector at approximately 1m from the horn. Initiate a new sweep.

```
TRIG:ARM  
TRACE:DATA ?
```

If needed, save the data to a file named S1.TXT.

Position reflector at approximately 2m from the horn. Initiate a new sweep.

```
TRIG:ARM  
TRACE:DATA ?
```

If needed, save the data to a file named S2.TXT.

If using data from a logged session, open the log file and copy the data to 3 text files, or into a spreadsheet, depending on your mathematical analysis software package.

Using a numerical analysis software package (for example Matlab or Mathematica) the acquired data can be plotted and processed. Plots of the three data files are shown in the following figures. As seen in Figures 3,4, and 5, the data is typically an oscillating signal with an amplitude of approximately 10e3 digital units. The closest echo appears to give the largest amplitude. Performing Fourier transformations on the data sets gives the spectral results shown in Figure 6. With a frequency span of 1500MHz, the resolution of the frequency bins will correspond to a distance of 0.1m (accounting for a two way path). As can be seen in Figure 7, the peaks are separated by approximately 10 bins, which corresponds to a shift in position of the reflecting sheet

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of 1m. It is also evident that all signals contain an echo positioned approximately at bin 16. This is most likely caused by the connection between the RF cable and the horn antenna. The 16 bins passed from the RF connector of the FMCW module and the connector of the horn relates to a one meter RF cable containing a PTFE dielectric, which gives an equivalent length in vacuum of approximately 1.6 meters.

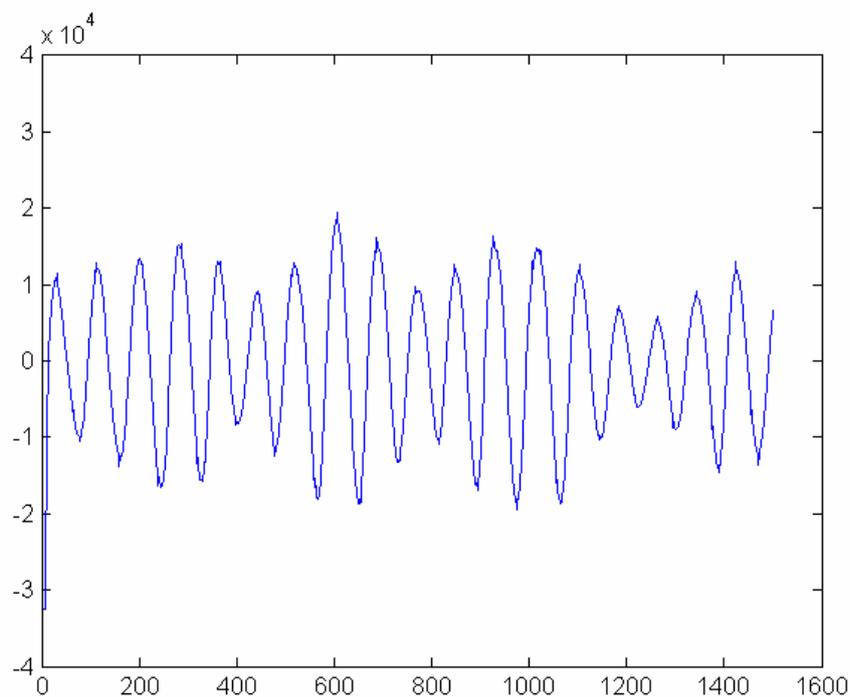


Figure 3. Plot of S0.TXT. Signal corresponds to a very close echo and possible reflections in the measurement equipment.

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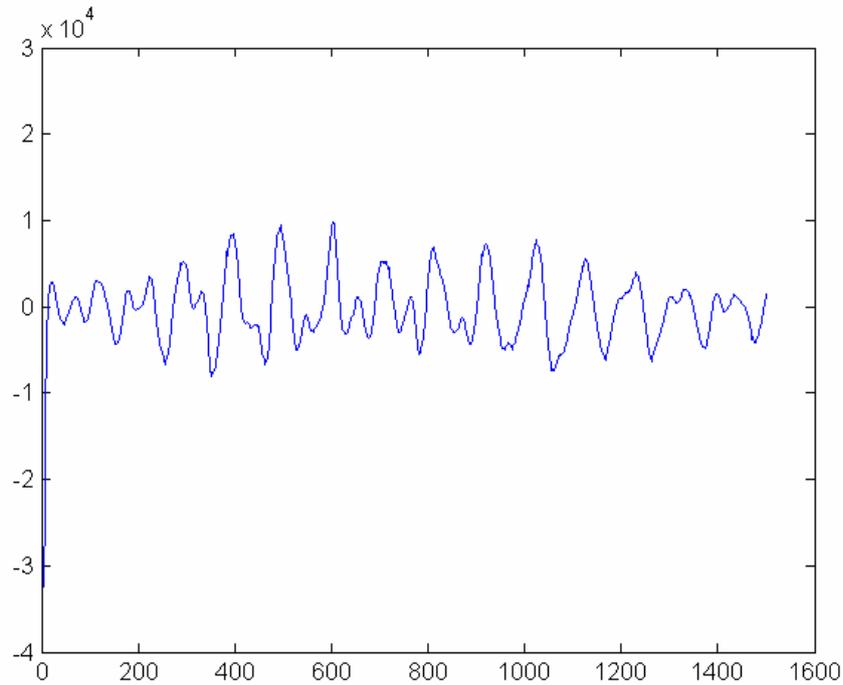


Figure 4. Plot of S1.TXT. Signal corresponds to an echo positioned approximately one meter away from the horn and possible reflections in the measurement equipment.

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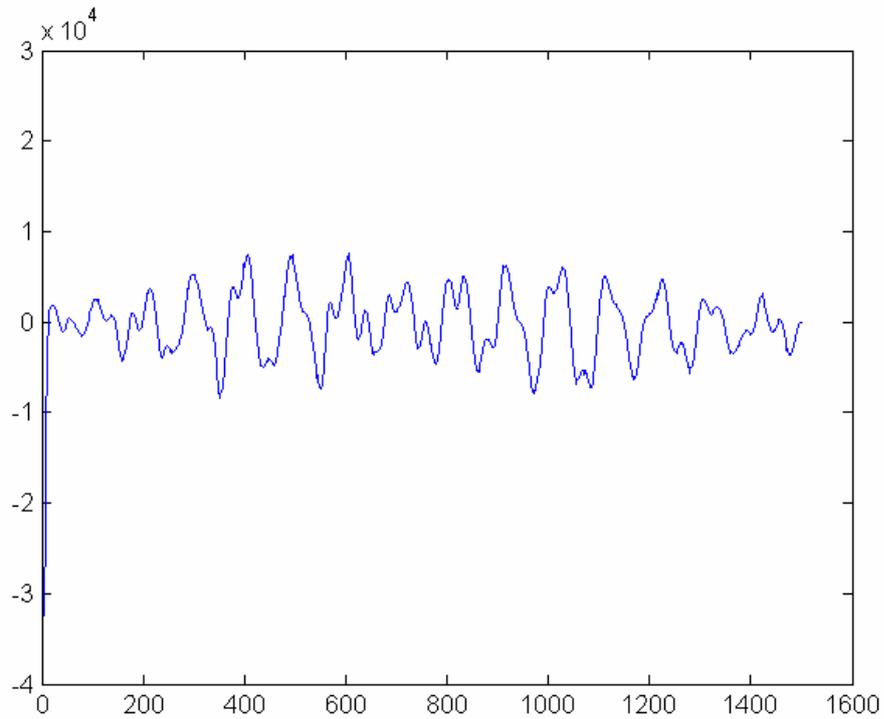


Figure 5. Plot of S2.TXT. Signal corresponds to an echo positioned approximately two meter away from the horn and possible reflections in the measurement equipment.

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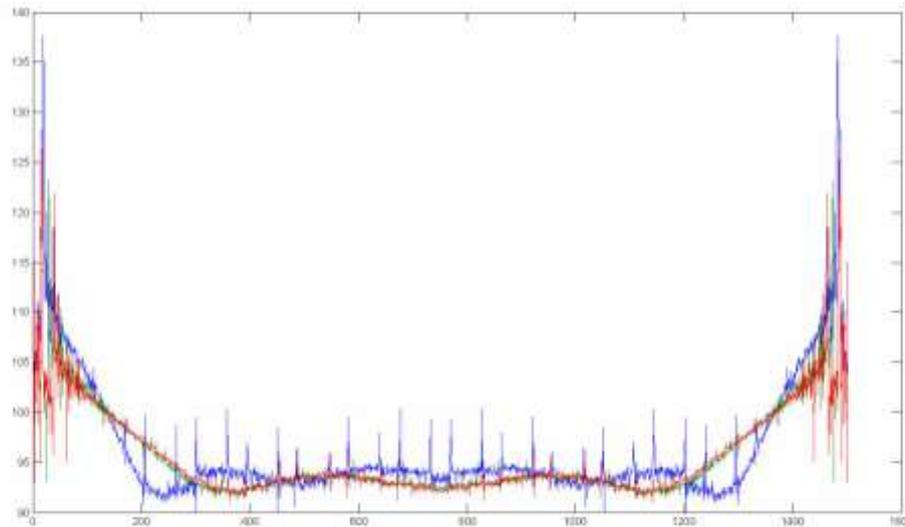


Figure 6. Plot of spectrum (absolute magnitude in dB).

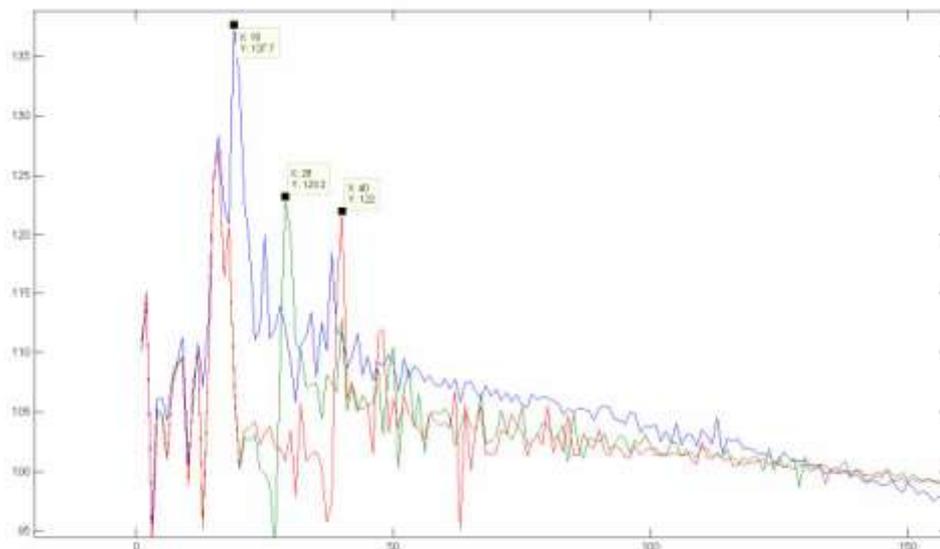


Figure 7. Close up of Figure 6, peaks indicated with markers.

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Controlling the FMCW unit using the CO1000A/00

The following section describes the commands that are available for controlling the evaluation kit. Communication can either be performed using a terminal program for manual control or by sending and receiving characters over the serial port using a program for automated measurements. When automated measurements are performed it is important to make sure that the input and output buffers are properly emptied when reading and sending characters.

Startup

When the unit is started a message is displayed, i.e., transmitted on the serial line:

```
SiversIMA AB
```

```
FMCW Eval board initialized
```

```
Software version: B RS3400K/02 2008-06-29
```

This means that the unit is ready to control the module and to perform measurements. The following text will briefly describe the commands that are available. Please note that this message is sent on the serial line regardless if there is a terminal window open or not. If an automated system is configured, this has to discard the message from the input buffer before reading any data from the unit.

Having local echo turned on in your terminal emulator may be helpful for entering commands.

Having session logging enabled may be useful for retrieving measurement data.

FMCW Radar Sensors

Commands available on the control board

All commands are built up in a hierarchical structure where there are seven main categories:

- FREQUENCY (control frequency setting parameters)
- HELP (provides a simple list of available commands)
- INIT (initializes the unit)
- MEASURE (controls measurement parameters)
- SWEEP (controls sweep parameters)
- TRACE (handles data generated by the unit)
- TRIGGER (controls trigger parameters)

Some main categories have sub-categories. These are reached by entering the main category and a colon ":" followed by the sub-category.

All categories where data can be entered can also return data, typically the previously entered data. Some categories can only return data, typically measurement data. Data is returned by entering the full category name (main:sub) followed by a question mark "?". Please note that there should be a space between the category name and the question mark.

All data, where applicable, is entered and returned in SI units, e.g., frequency is entered in Hz and time is entered in seconds.

Commands are not case sensitive.

FMCW Radar Sensors

Main categories

FREQUENCY

Controls frequency setting parameters. Note: several parameters are related and the setting of one parameter may change the setting of others. As an example, changing SPAN will affect both START and STOP.

Under categories.

CENTER

Sets the center frequency of the sweep.

Usage:

```
FREQUENCY: CENTER 24.7e9  
FREQUENCY: CENTER ?
```

Default: 24.75e9 (24.75GHz)

SPAN

Sets the frequency span of the sweep.

Usage:

```
FREQUENCY: SPAN 500e6  
FREQUENCY: SPAN ?
```

Default: 1.5e9 (1.5GHz)

START

Sets the start frequency of the sweep.

Usage:

```
FREQUENCY: START 24.4e9  
FREQUENCY: START ?
```

Default: 24.0e9 (24.0GHz)

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STOP

Sets the stop frequency of the sweep.

Usage:

```
FREQUENCY:STOP 25.4e9
```

```
FREQUENCY:STOP ?
```

Default: 25.5e9 (25.5GHz)

STEP

Sets the frequency step, i.e., frequency separation between two contiguous frequency points of the sweep.

Usage:

```
FREQUENCY:STEP 0.5e6
```

```
FREQUENCY:STEP ?
```

Default: 1e6 (1MHz)

Max: -

Min: 8e3 (8kHz)

POINTS

Sets the number of frequency points to use during a sweep.

Usage:

```
FREQUENCY:POINTS 301
```

```
FREQUENCY:POINTS ?
```

Default: 1501

Max: 1501

HELP

Provides a simple list of available commands.

Under categories

None.

INIT

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Initializes the RS3400 unit. Does not restore variables to default.

Under categories
None

MEASURE

Controls measurement parameters.
Under categories

CHANNEL

Sets the channel to be used when measuring during a frequency sweep. This feature is currently not active.

SWEEP

Controls sweep parameters. Note: several parameters are related and the setting of one parameter may change the setting of others. As an example, changing TYPE will affect the number of data points acquired when a measurement is performed and TIME will affect IDLE.
Under categories

TYPE

Sets the type of sweep to be performed. Available types are SAWTOOTH and TRIANGULAR. The type SAWTOOTH is a sweep of linearly increasing frequency. When the highest frequency is reached, the sweep restarts at the lowest frequency. The type TRIANGULAR is a sweep of first linearly increasing frequency and then linearly decreasing frequency. The sweep then restarts with an increasing frequency.

When a measurement is made during a TRIANGULAR sweep, data is recorded both on the positive and the negative frequency slope. Thus the number of data points is twice that of SAWTOOTH and also twice of what is entered at `FREQ:POINTS`.

Usage:

```
SWEEP:TYPE TRIANGULAR  
SWEEP:TYPE ?
```

Default: SAWTOOTH

NUMBERS

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Defines the number of frequency sweeps to be performed when triggered. The measurement of the IF signal is averaged over the number of sweeps. If 0 is entered, the sweep continues indefinitely, but can be aborted by sending a capital Q. Please note that the currently started sweep will be finished and communication with the unit is not possible before that.

Usage:

SWEEP:NUMBERS 5

SWEEP:NUMBERS ?

Default: 0 (infinite number of sweeps, finish with "Q")

MEASURE

Defines whether a measurement of the IF signal should be performed during the sweep or not.

Usage:

SWEEP:MEASURE ON

SWEEP:MEASURE ?

Default: OFF

TIME

Sets the total time for a complete sweep. This time should be chosen long enough to allow a sufficient time at each frequency point, see SWEEP:IDLE.

Usage:

SWEEP:TIME 1.0

SWEEP:TIME ?

Default 0.075 (75ms)

IDLE

Defines the time spent at each frequency point. In principle, the RF frequency is set at the beginning of this time and a measurement of the IF signal is performed at the end of this time.

Usage:

SWEEP:IDLE 10e-3

SWEEP:IDLE ?

Default: 50e-6 (50 μ s)

Min: 50e-6

Max: 1

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Please note that a high setting of IDLE time will give a very long frequency sweep when the number of frequency points is big.

TRACE

Controls data generated by the unit.

Under categories

DATA

Returns measurement data. Data is an array of floating point numbers. The array length is controlled by SWEEP:NUMBERS (see SWEEP).

Usage:

TRACE:DATA ?

Please note that TRACE:DATA ? will return data for a complete measurement. The number of lines that are returned is controlled by FREQUENCY:POINTS and SWEEP:TYPE. If SWEEP:TYPE is set to TRIANGULAR, twice the number of data points is returned.

This may overflow the input buffer of the serial connection of the computer if it is not set up correctly.

The output will be ended with a separate line containing OK indicating that transmission is completed.

TRIGGER

Controls trigger parameters.

Under categories.

SOURCE

Defines the source that will trigger the start of a frequency sweep. Available settings are IMMEDIATE, meaning that no trigger signal is necessary, and EXT0. The EXT0 is connected to the Trigger input pin of the control board. A transition from low (0V) to high (3.3V) will trigger a measurement.

Usage:

TRIGGER:SOURCE IMMEDIATE

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TRIGGER:SOURCE ?

Default: IMMEDIATE.

ARM

Puts the unit in a state ready to start the defined frequency sweep. Certain parameters are calculated and the module is set to the start frequency. If TRIGGER:SOURCE is set to IMMEDIATE, the frequency sweep is started as soon as the unit has completed the necessary preparations.

Usage:

TRIGGER:ARM

OUTPUT

Defines whether or not a trig signal should be output when a frequency sweep starts. Trigger output is available as a 0/3.3V signal on the Trigger out on the control board.

DELAY

Sets the length of output trigger pulse. The actual frequency sweep does not start until the trigger pulse has completed and consequently this can be used as a delay between input trigger and actual start of the frequency sweep. If a trigger output is enabled, it will be issued for each single sweep.

Usage:

TRIGGER:DELAY 10e-3

TRIGGER:DELAY ?

Default: 10e-3 (10ms)

Min: 50e-6

Max: 1

FMCW Radar Sensors

Example of using the 3-wire interface

Desired parameters :

Frequency Range : 9.5 ~ 10.5GHz
Frequency Step : max (guaranteed RS3400X/00)
Sweep Time : 10ms
Sweep Type : SAWTOOTH

Required 3-wire commands:

Given 10ms for a 1GHz sweep, a 5MHz step and a frequency idle time of 50 micro seconds is recommended. This will generate 201 frequency points (accounting for start and stop). The complete sweep time will then be 10.05 ms.

Communication with the FMCW module uses the MicroWire protocol, using Clock, Data and Latch Enable (LE) signals. Data is sent in 32bit words, MSB first. Data is clocked on rising edge of Clock. The word is latched with a high pulse of LE (the LE pin should be held low during data transfer). The LE pulse should be a minimum of 3 ms during the boot sequence and a minimum of 50 ns during frequency setting.

The boot sequence would be as follows (please remember the 3ms latch length):

```
0x0000 0004  
0x0000 4003  
0x0540 fffa  
0x1868 2aa8
```

Thereafter, frequency is programmed with a word defined as:

```
0x1800 0000 + N*8
```

where N is an integer and $N*11718.75$ defines the output frequency in Hz. The last line of the boot sequence programs the frequency of 9,999 996 093.75 Hz, the closes frequency to 10.0 GHz possible. Programming 9.5GHz would send the word 0x1862 f550 and programming 10.5GHz would send the word 0x186d 6000.

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For direct control of the module, along with IF output logging, LabVIEW software may be helpful, using some type of PC interface for the 3 wire / SPI protocol. National Instruments, for example, produces a USB compatible module (NI USB-8451) allowing for easier interfacing, control and programming between the PC and SPI devices.

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