

Lab Manual:  
Communications Principles  
  
Using the EMONA Communications board for NI ELVIS III



Lab 17: Carrier regeneration with the Costas Loop

List of Updates

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# Lab 17: Carrier regeneration with the Costas Loop

## Learning Objectives

After completing this lab, you should be able to complete the following activities.

1. Build a Costas loop
2. Regenerate a carrier signal from carrier-less incoming signal
3. Understand the effect of the control voltage on the VCO
4. Appreciate the necessity of tuning the loop VCO
5. Recover from both analog and digital signals
6. Understand the basics of loop analysis

## Prerequisites

You should have completed Lab 1 and Lab 2 and be familiar with the equipment, its use and the handling precautions for the equipment.

## Required Tools and Technology

|  |  |
| --- | --- |
| Platform: NI ELVIS III Instruments used in this lab:   * Oscilloscope-Time * Oscilloscope-FFT * Function Generator | * Access instruments <https://measurementslive.ni.com> * View User Manual <http://www.ni.com/en-us/support/model.ni-elvis-iii.html> * View tutorials <https://www.youtube.com/playlist?list=PLvcPIuVaUMIWm8ziaSxv0gwtshBA2dh_M> |
| Hardware: Emona Communications Board Components used in this lab:   * Four BNC to 2mm banana-plug leads * Assorted 2mm banana-plug patch leads * Set of headphones or earbuds | * View User Manual <http://www.ni.com/en-us/support/model.emona-communications-board-for-ni-elvis-iii.html> |

## 

## Expected Deliverables

In this lab, you will collect the following deliverables:

* Calculations
* Data from measurements
* Observations

Your instructor may expect you complete a lab report. Refer to your instructor for specific requirements or templates.

## Section 1: The basic Costas loop

## Theory and Background

This loop, and its variations, is much-used as a method of carrier acquisition (and simultaneous message demodulation) in communication systems, both analog and digital. It is named after J. P. Costas, a pioneer in synchronous communications.

It has the property of being able to derive a carrier from the received signal, **even when there is no component at carrier frequency present in that signal** (eg, DSBSC or BPSK). The requirement is that the amplitude spectrum of the received signal be symmetrical about this frequency.

The basic Costas loop is illustrated in Figure 1.



Figure 1: Block diagram of basic Costas Loop

The Costas loop is based on a pair of quadrature modulators - two multipliers fed with carriers in phase-quadrature. These multipliers are in the in-phase (I) and quadrature phase (Q) arms of the arrangement.

Each of these multipliers is part of separate synchronous demodulators. The outputs of the modulators, after filtering, are multiplied together in a third multiplier, and the lowpass components in this product are used to adjust the phase of the local carrier source - a VCO - with respect to the received signal.

The operation is such as to maximise the output of the I arm, and minimize that from the Q arm. The output of the I arm happens to be the message, and so the Costas loop not only acquires the carrier, but is a (synchronous) demodulator as well.

A complete analysis of this loop is non-trivial. It would include the determination of conditions for stability, and parameters such as lock range, capture range, and so on. A simplified analysis is given at the end of this experiment.

Although the Costas loop can provide a signal at carrier frequency, there remains a 1800 phase uncertainty.

A phase ambiguity of 1800 in many (typically analog) situations is of no consequence - for example, where the message is speech. In digital communications it will give rise to data inversion, and this may not be acceptable - but there are methods to overcome the problem ie: line coding the data eg NRZ-M so that it is immune to inversion.

## 1.2 Implement: Setting up the signals to be acquired

In most of the experiments involved with demodulation a stolen carrier is used. This allows full attention to be paid to the performance of the demodulator. Considerations of how to acquire a carrier from the received signal are ignored.

In this experiment, following a similar principle, attention will be paid to the means of acquiring a carrier from a DSBSC signal, without paying attention to the subsequent performance of the device for which the carrier is required (eg, a demodulator).

The experiment to follow is described in outline only. It will take you only to the point at which the carrier is acquired.

It should take you about 45-60 minutes to complete this experiment.

**Powering up the ELVIS III + EMONA Communications Board**

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| --- | --- |
| 1. | Ensure that the NI ELVIS III Application Board power button at the top left corner of the unit is OFF (not illuminated). |

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| --- | --- |
| 2. | Carefully plug the Emona Communications board (ECB) into the NI ELVIS III ensuring that it is fully engaged both front and back. |

|  |  |
| --- | --- |
| 3. | Ensure that you have connected the NI ELVIS III to the PC using the USB cable and that the PC is turned on. |

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| 4. | Turn on the Application Board *Power* button by pressing it once and confirm that it is illuminated. The LEDs on the ECB should also be illuminated. If they are not, then switch the unit off immediately and check for connection or insertion errors. |

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| 5. | Open the Instrument Launcher software in your browser and select and RUN the following instruments. |

Scope Configuration

|  |  |
| --- | --- |
| Channel Voltage range | 1V/div |
| Horizontal Timebase | 1us/div |
| Trigger | Type: Analog edge, Source: Channel 1 input, Rising |
| Probe Attenuation | 1x |

6. Obtain a DSBSC signal based on a carrier at 100 kHz. Here is a brief reminder about doing this:

To create DSBSC: Multiply the 2.08kHz SINE signal with 100kHz COS, using MULTIPLIER 2 (DC inputs).

To create BPSK: Clock SEQUENCE GENERATOR 1 with 2.08kHz DIGITAL. Multiply the analog X output with 100kHz COS, using MULTIPLIER 2 (DC inputs).

Both these signals have a symmetrical spectrum and no 100kHz carrier component.

However they have different messages: The DSBSC has an analog message, whereas the BPSK has a digital message stream. This makes for some variety in the recovery process.

## 1.3 Implement: Setting up the Costas loop

8. Set the VCO output frequency to as close to 100kHz as you can, using the FREQ control. Set the GAIN control to minimum (0). Use the scope set to 1 us/div so you can closely view the period of the signal accurately.

8. Next, before doing any other patching, set up the PHASE SHIFTER module to provide a -90 degree phase shift. The PHASE SHIFTER is optimized to work in the 100kHz frequency range only. Input the 100kHz COS signal into the PHASE SHIFTER and view both the input and output of this module with Channels 1 & 2 of the scope. Once the output of the PHASE SHIFTER is a SINewave, then you have the -90 degree shift required. Note that in quadrature modulation work, the I (in-phase) branch is normally associated with a COSine, whereas the Q (out-of-phase) branch is associated with the SINewave component.

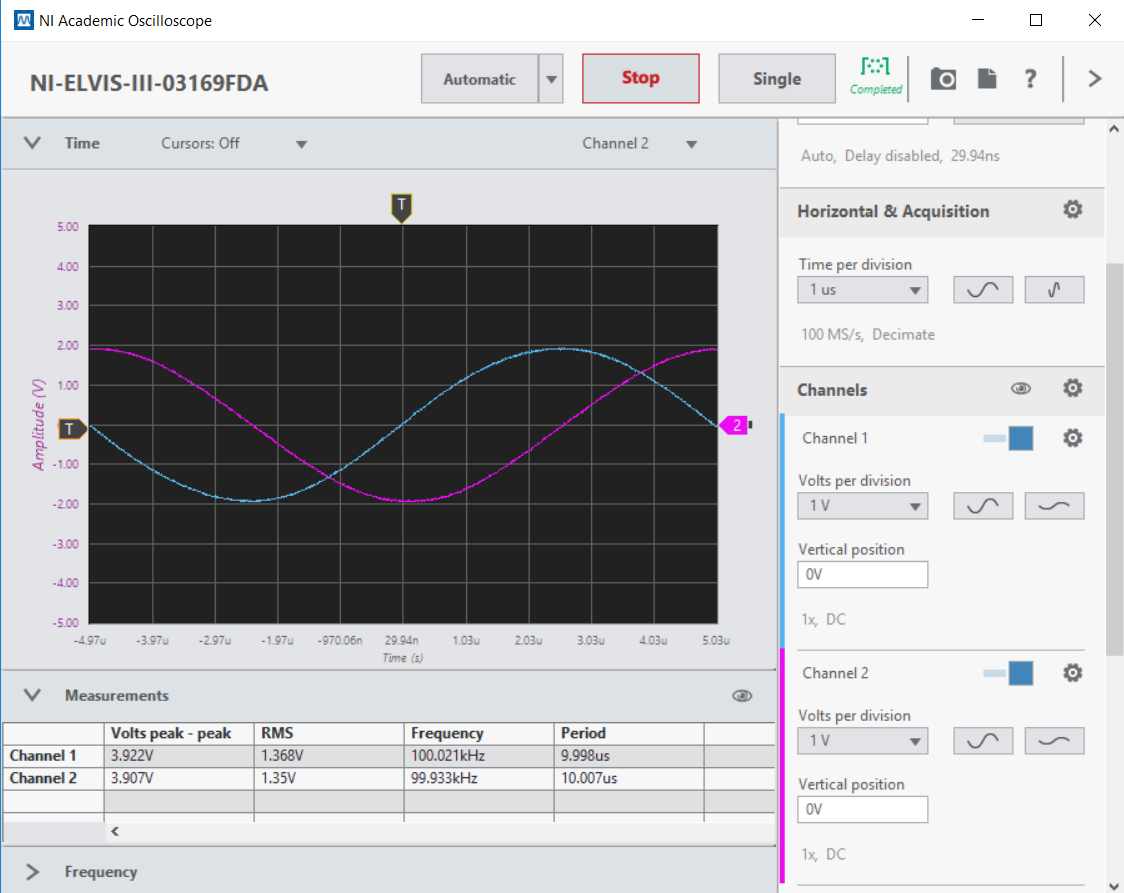


Figure 2: Example of 90 degree phase shift: I=cos; Q=sin

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| --- | --- |
| 7. | Connect the rest of the set-up shown in Figure 2 below.  **Note:** Insert the black plugs of the oscilloscope leads into a ground (*GND*) socket. |

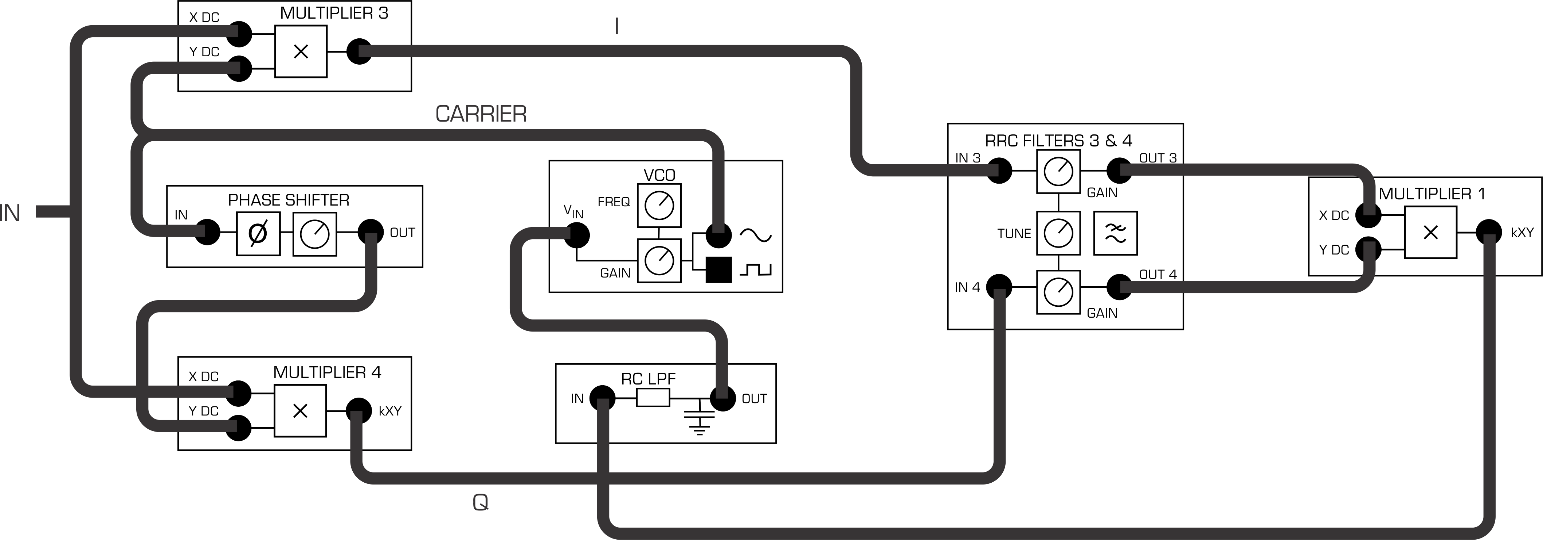


Figure 3: Patching for Costas Loop

8. Use RRC FILTERS 3 & 4 for the filters in the I and Q arms. Set both their GAINS to minimum, and their shared TUNE control to maximum bandwidth.

* 1. Why are the filters set to maximum bandwidth?

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9. The RC LPF module is used to filter the control signal to the VCO. The “loop” filter typically used for these purposes has a very low cutoff frequency and a simple phase response. The TUNEABLE LPF would NOT be a suitable “loop” filter. The RC LPF is not ideal but will do for our purposes.

10. Check the amplitudes at all module interfaces and confirm that none of them are overloaded. Set Channel 1 & 2 of the scope to the 100kHz COS carrier and the VCO output carrier. These are both approximately 100kHz but are not synchronized to each other and will be drifting slowly relative to each other.

11. To tune the loop, slowly increase the VCO gain until the VCO locks to the DSBSC carrier, as indicated by the oscilloscope traces becoming stationary with respect to each other.

12. Observe the demodulated output from the filter of the I arm. If lock has been achieved, but the demodulated waveform (the message) is other than the message, fine tune the VCO while still locked. The frequency won`t change (it is locked to the carrier) but this will result in a ‘cleaner’ and smaller control signal to the VCO, and a maximum amplitude minimum-distortion demodulated output.

You will notice that lock is achieved when the VCO gain setting is above a certain minimum value. If the gain is increased ‘too far’, the lock will eventually be lost. From the behaviour of the VCO output signal (or otherwise) during this procedure, can you explain the meaning of ‘too far’?

13. Open and close the connection from the DSBSC signal to the input of the Costas loop, and show that carrier acquisition is lost and regained. Although lock may appear to happen ‘instantaneously’ it will in fact take a finite number of carrier cycles after the connection is made. Note that the phase difference between the reference and recovered carrier takes one of two values, 180 degrees apart. This phase ambiguity of the acquired carrier is associated with many carrier acquisition schemes.

14. Try changing the message signal to the BPSK signal option and examine the various points around the loop.

## 1.2 Implement: Measurements & VCO emulation

There are many measurements and observations that could now be made. This will depend upon the level of your course work.

15. View the VCO control voltage AND the recovered message on the I branch at the same time. They both use the same scope timebase. Vary the VCO GAIN control and observe these signals as the loop goes in and out of lock.

* 1. What level does the control voltage have during lock versus when out of lock ?

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* 1. What happens to lock if you swap the inputs to the I & Q filters, or swap the outputs from the I & Q filters?

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Of practical interest would be a knowledge of the loop acquisition time under different conditions, lock range, holding range, conditions for stability, and so on. These dynamic measurements require more sophisticated instrumentation than you probably have.

Thus it is suggested that you confine your observations to checking that the loop actually works (already done), and some less sophisticated measurements.

A technique of interest is to replace the VCO signal with a ‘stolen’ carrier connected into the loop. This “stolen” carrier should be either the 100kHz SINE signal or the 100kHz COS signal from the MASTER SIGNALS module This emulates the locked VCO and allows static observations of all points of the loop for various values of the phase angle . Appendix A to the experiment gives and exact analysis of this condition.

In particular, the control signal to the VCO can be monitored.

You are looking for the condition where the magnitude of the control signal is a minimum. This must be the condition when final lock is achieved, since any other value would tend to move the VCO until it was met.

It is best to use a message frequency as high as possible so as not to confuse the measurement of the DC control signal with the unavoidable unwanted terms.

The analysis shows that every time a signal is processed by a multiplier followed by a filter there is an amplitude reduction of the signal under observation of one half due to the analytic process, and due to the ‘k factor’ of each MULTIPLIER module. Squaring the message introduces another reduction of one half.

Remember, then, that you will be looking for quite small signals, especially the DC control to the VCO.

## Section 2: Appendix A

## 2.1: A simplified analysis

A simplified analysis of the Costas loop (Figure 1) starts by assuming that a stable lock has already been achieved.

This in turn assumes that the VCO is operating at the correct frequency, but that its relative phase is unknown. Call the angle  the phase difference between the received carrier and the VCO.

Let the received DSBSC be derived from the message m(t), and based on a carrier frequency of  rad/s. This then is also the frequency of the VCO when locked.

If the ‘k factor’ of the MULTIPLIER modules is included then the following analysis holds. (Keep in mind that the MULTIPLIERS actual k factor = approx.. 1.)

Define the signals into the multipliers of the I and Q arms as I andQ. Then:

|  |  |  |
| --- | --- | --- |
| *I*  = | m(t).k.cost.cos(t + ) | ........  A-1 |
| *Q*  = | m(t).k.cost.sin(t + ) | ........  A-2 |

Equations (A-1) and (A-2) may be expanded, and only the low frequency terms retained, to obtain the signals from the lowpass filters. These go into the ‘third’ multiplier. Let these be named *ILF*: and *QLF*. Then:

|  |  |  |
| --- | --- | --- |
| *ILF*  = | ½.m(t).k.cos | ........  A-3 |
| *QLF*  = | ½.m(t).k.sin | ........  A-4 |

After these are multiplied together, the output of the ‘third’ multiplier is:

|  |  |  |
| --- | --- | --- |
| *‘third’ mult out*  = | ½.¼.m2(t).k2.sin2 | ........  A-5 |

No matter what the message m(t), the square of it will be positive, and contain a DC component, which can be filtered off.

If the message is a sine wave, and the DSBSC amplitude is unity, then:

|  |  |  |
| --- | --- | --- |
| *filter output*  = | . | ........  A-6 |

The DC from the filter has a magnitude which is a function of the phase error . This DC is the control signal to the VCO. It can change sign, according to the magnitude of . Providing the loop is stable the tendency will be to shift the phase of the VCO until  is reduced to zero, since only then will the VCO come to rest.

## 2.2 message output

The message appears at the output of each of the I and Q filters. But under lock condition the phase error  will be zero, and eqns. A-3 and A-4 tell us that the message amplitude at the output of the I filter will be maximized, and minimized at the output of the Q filter.