# PHYS2641 – Laboratory Skills and Electronics

## Electronics

### Lecture 5

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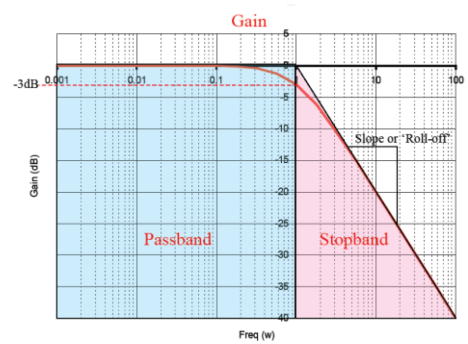
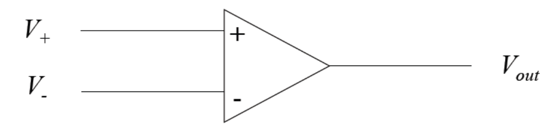
# Recap – last year:

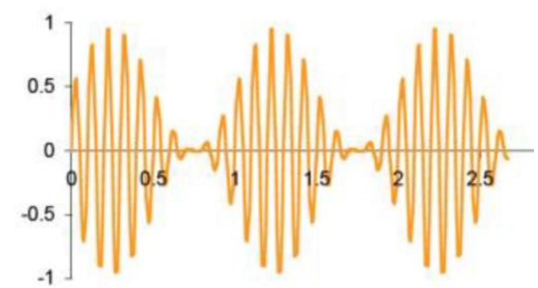
- Passive filters



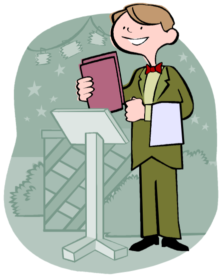

- Op-amp circuits




- Modulated signals



# Today’s menu



Aims:

1. Noise in analog systems
2. Phase-sensitive (lock-in) detection

# Noise: definition

- Noise can be generally defined as any source of ‘data’ which are not desirable in the ‘experiment’, e.g.
  - Background chatter in a lecture theatre
  - Interference on a radio signal
  - Mains ‘hum’ (50Hz pick-up) on your oscilloscope traces
- Signal-to-noise ratio (SNR) is simply defined as the ratio of the useful to the non-useful data:

$$\mathrm{SNR} = \frac{V_{signal}}{V_{noise}}$$

$$\mathrm{SNR}_{dB} = 20\log_{10}\left(\frac{V_{signal}}{V_{noise}}\right)$$

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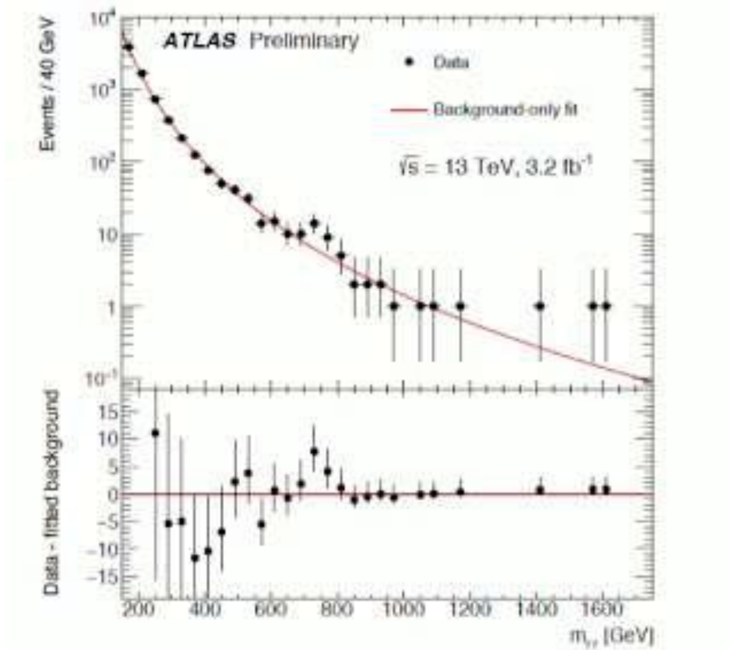
# Noise reduction - averaging





PRL 116, 150001 (2016) PHYSICAL REVIEW LETTERS week ending 15 APRIL 2016


**Editorial: Theorists React to the CERN 750 GeV Diphoton Data**

Last December, the ATLAS and CMS Collaborations at the Large Hadron Collider reported preliminary data with a small excess of diphoton events at an invariant mass of about 750 GeV [1,2], which, if verified, would require unexpected new elementary particles. The collaborations have recently reanalyzed their data [3,4], and the signal has become slightly stronger. Though the results are extremely intriguing, more data are required to establish if the excess is real, or a statistical fluctuation.

Over 250 theory papers have appeared following the December announcement, and a number of them were submitted to us. We found it appropriate to publish a small sample of them. To maximize the coherence and fairness of our choices, we obtained informal advice from several experts.

Four such Letters appear in this issue [5–8]. Others may follow, but we think that this set gives readers a sense of the kind of new physics that would be required to explain the data, if confirmed.

Robert Garisto
Editor


Published 12 April 2016
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Random noise can be reduced by **averaging**

It is a good idea to do this before announcing your results to the international news media…

# Johnson noise

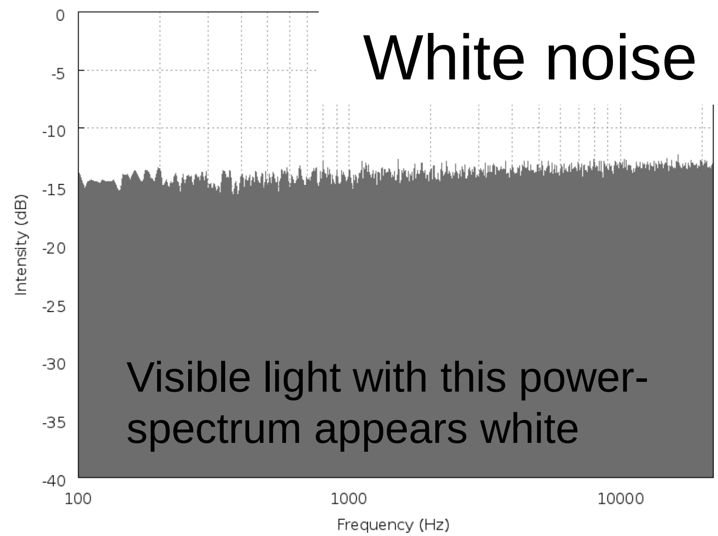
Johnson noise is due to thermal motion of electrons, giving voltage noise

$$V_{noise}\left(\mathrm{RMS}\right)=\sqrt{4k_BTRB}$$

and current noise

$$I_{noise}\left(\mathrm{RMS}\right)=\frac{\sqrt{4k_BTRB}}{R}$$

where B is the noise bandwidth (Hz)




We can reduce Johnson voltage noise by reducing the ‘device’ resistance

Alternatively, we can reduce Johnson current noise by increasing resistance

We can also reduce Johnson noise by reducing temperature; but this is not always practical

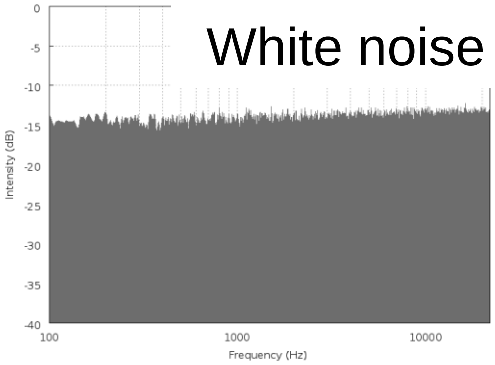
# Shot noise

Shot noise occurs due to the quantised nature of electric charge

The passage of individual electrons can be observed as ‘shot noise’ in very low-current measurements

The RMS current noise is $$I_{noise}\left(\mathrm{RMS}\right)=\sqrt{2eI_{dc}B}$$

Shot noise also has a ‘white’ power spectrum

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# 1/f noise

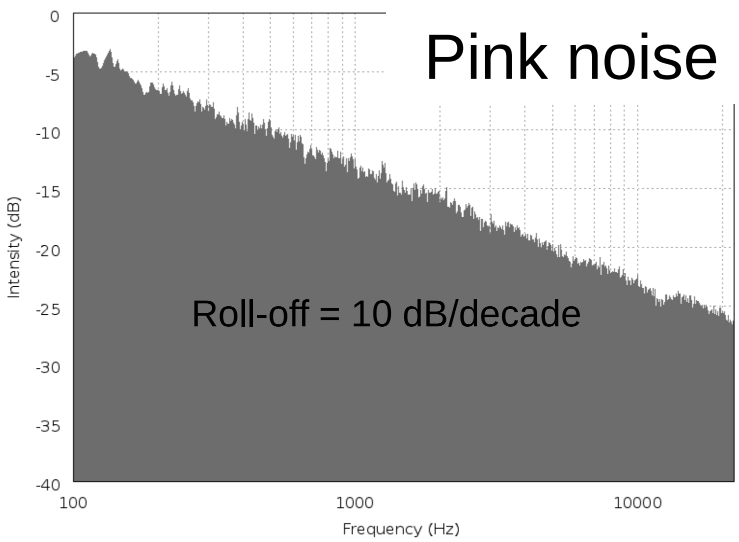
Often referred to as 'pink' noise or 'flicker' noise: it is the most common noise source

1/f noise arises in many 'natural' systems:

Noise in a room

Waves on the sea

Behaviour of financial markets...




Visible light with this power-spectrum appears pink

In electronic systems, 1/f noise originates from **thermally-activated fluctuations** in material properties in a circuit; e.g. carrier activation in a semiconductor

Pink noise is less 'hissy', more 'rumbly' that white noise

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# 1/f² noise

Brown (red) noise arises due to Brownian motion and is sometimes called ‘random-walk’ noise

Brown noise can be produced by adding a random offset to each sample (measurement) to obtain the next

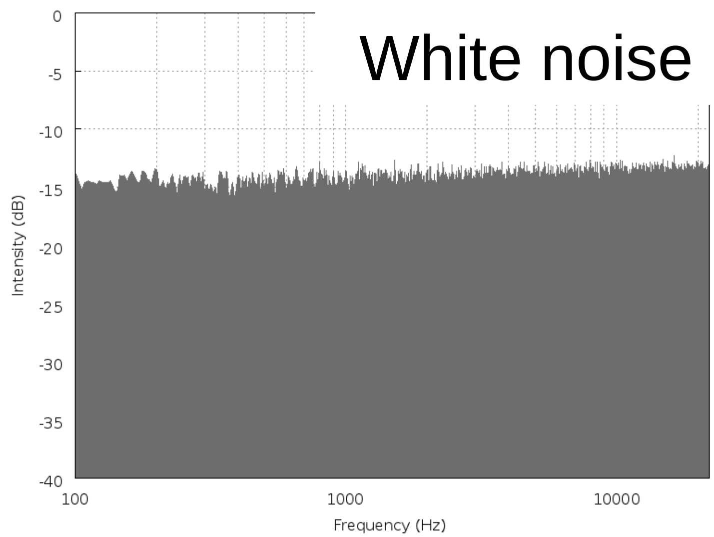
Brown noise is generally dominated by 1/f noise at low frequency, and is dominated by white noise at high frequency

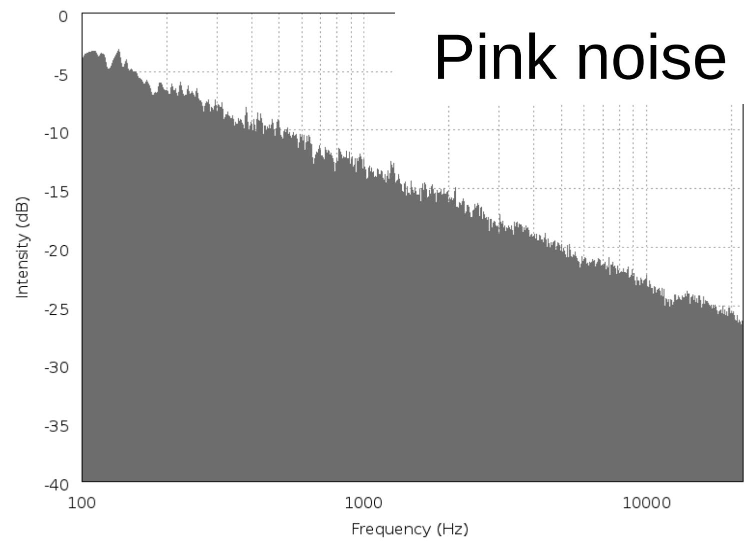
Brown noise


Visible light with this power-spectrum appears red/brown

Brown noise is more ‘roaring’ that pink noise; like a waterfall!

# Dominant noise source




At low frequencies, 1/f noise dominates – higher ‘noise power’ (Intensity)

At high frequencies white noise dominates: noise power is constant

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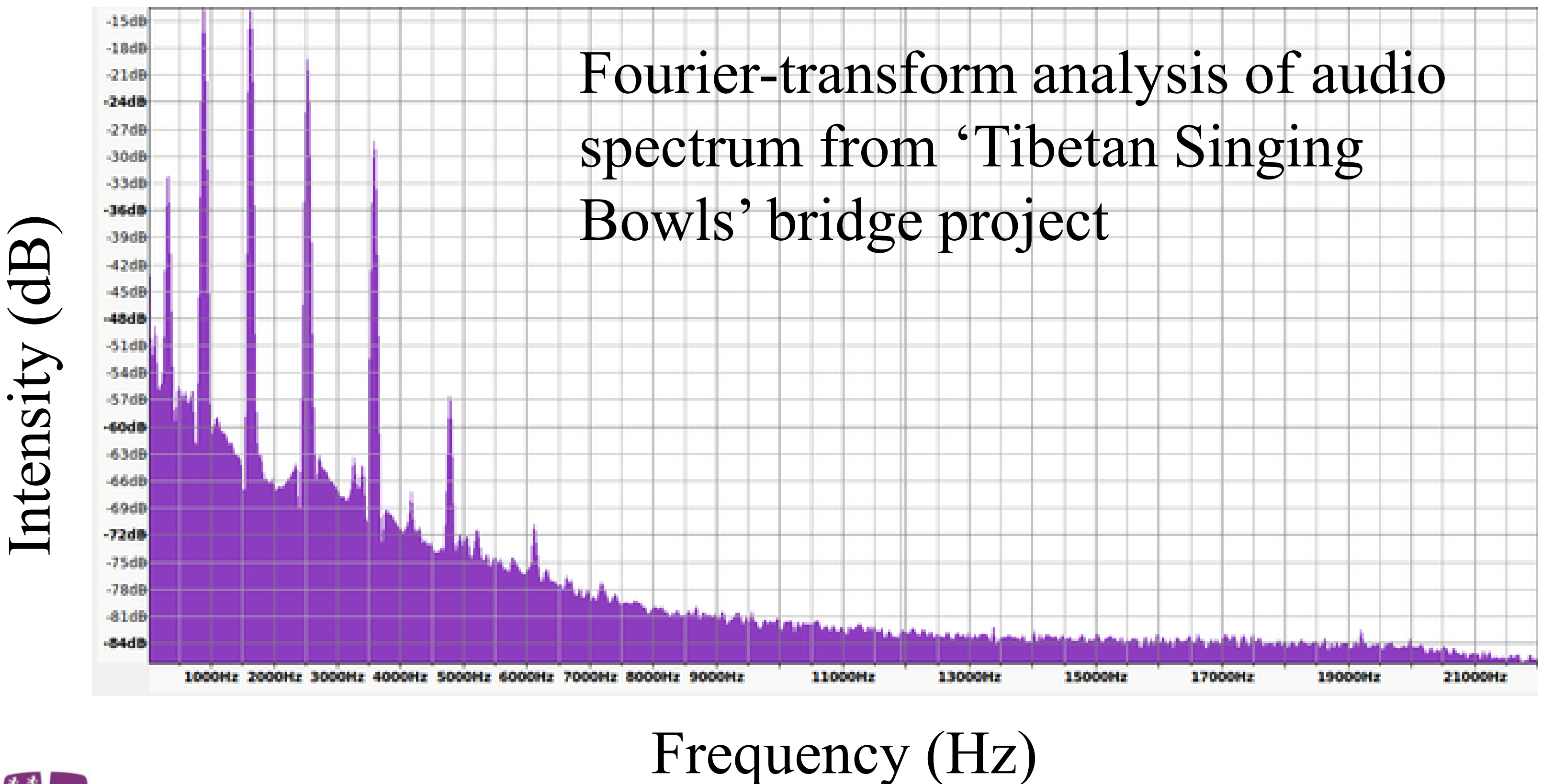
# Background noise – example




Fourier-transform analysis of audio spectrum from ‘Tibetan Singing Bowls’ bridge project

Astronomy

# Microwave oven to blame for mystery signal that left astronomers stumped

Australian scientists first detected interference in 1998, which they assumed was from lightning strikes, but earlier this year they finally found the real culprit

Monica Tan

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Tuesday 5 May 2015 08.21 BST



The source of 'suspicious perytons' that caused headaches for astronomers at the Parkes radio telescope for years has finally been identified. Photograph: Julian Chang/Guardian Australia

The mystery behind radio signals that have baffled scientists at Australia's most famous radio telescope for 17 years has finally been solved.

The signals' source? A microwave oven in the kitchen at the Parkes observatory used by staff members to heat up their lunch.

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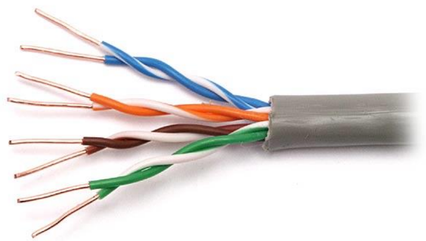
# Noise reduction

- Use larger signal amplitude – V rather than μV-mV to improve SNR
- Use shielding: coaxial cables or 'twisted pairs' rather than plain wires, put sensitive circuits in grounded metal boxes (or Faraday cage)



- Noise can always be reduced by **decreasing the bandwidth** of the measurement: e.g. use filtering to remove high or low frequency noise

Noise bandwidth is reduced significantly by using **lock-in detection...**

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# Lock-in amplifiers

A lock-in amplifier (LIA) measures the ***amplitude*** of ***very faint modulated signals*** in the presence of (potentially a large amount of) noise

It uses a process known as ***lock-in detection*** or ***phase-sensitive detection***

LIAs are one of the most useful tools in experimental physics

Your assessed practical involves measuring a faint, noisy, signal using lock-in detection

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# Lock-in detection: concept

It is easier to 'detect' an AC (alternating/modulated) signal than a DC signal:

Flashing lights; Two-tone sirens; 'Twinkling' stars in the sky

We can convert any signal to an AC signal using (amplitude) modulation:

- Optical signals can be modulated by switching the beam on/off periodically or breaking the beam using a 'chopper'
- Electrical etc. signals can be modulated by multiplying by an AC carrier signal

We then use our prior knowledge of the carrier signal to let us 'reject' unwanted signals – i.e. to 'lock-in' to the modulation frequency

Note: the 'signal' does not have to be DC – also AC (as in modulation examples) or any voltage signal with sufficiently low frequency Fourier components

# Lock-in detection: concept (2)

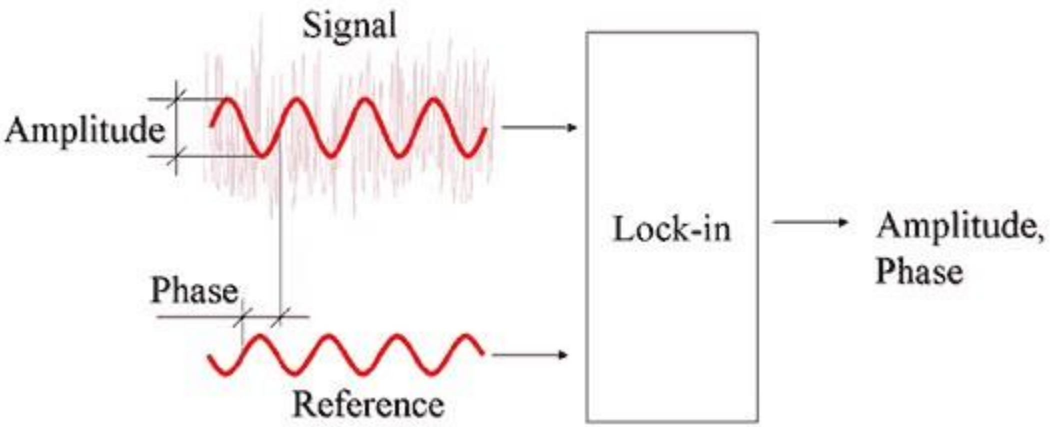
A LIA can be thought of as a detector with an extremely narrow-band filter; rejects noise at almost all frequencies

This narrow-band filter selects only the component of the (noisy) input signal waveform that have a specific

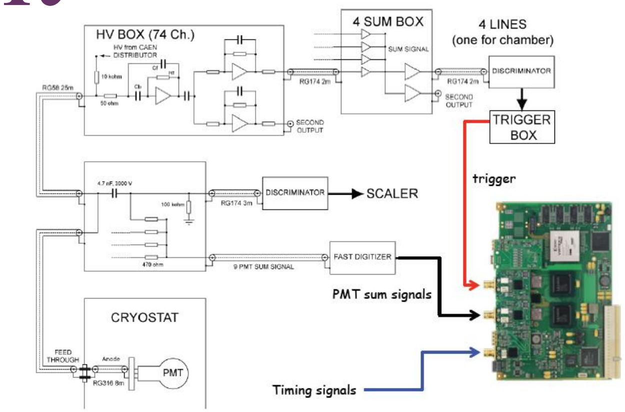
**FREQUENCY**

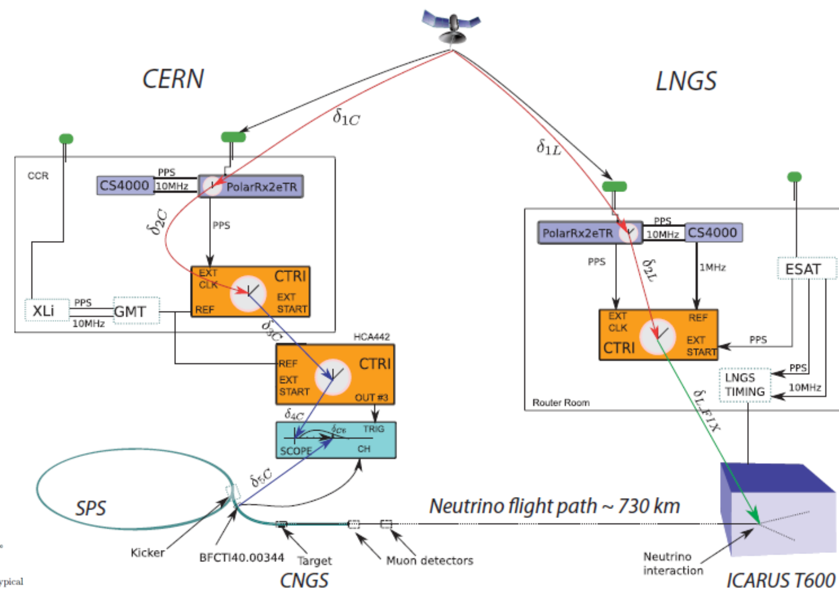
and

**PHASE** (hence the name 'phase-sensitive' detection)



# Aside: 'Faster-than-light' neutrinos...



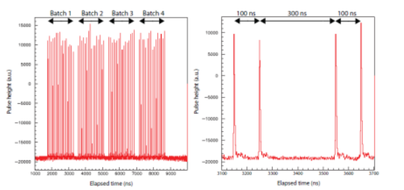



Figure 1. CNGS proton beam structure dedicated to neutrino time of flight measurement. Typical width of each proton pulse is ~ 4 ns (FWHM).

Figure 2. Schematics of the 2011 CERN-LNGS timing synchronization. The origin of the neutrino time of flight measurement is at BFCTT40. For ICARUS, the arrival reference point is the T600 entry wall.

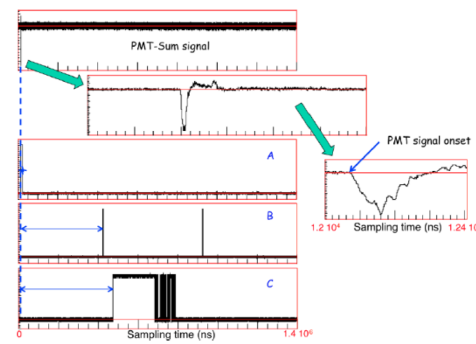



Figure 6. Example of signals recorded on the ICARUS PMT-DAQ: (A) TTL signal generated in the ICARUS trigger box (5 ns front edge, 10 μs wide): also sent to HPTF and WR-DAQ for time stamp; (B) 2 kHz signal from WR fine-delay (1 μs wide, 3 ns front edge): defines absolute time in WR time bases and monitors Acqiris time stability; (C) 1 kHz (PPmS) ESAT timing signal (200 μs wide, 3 ns front edge, followed by time encoding): defines absolute time in LNGS time base.

Lock-in detection using a proton synchrotron and underground neutrino detector

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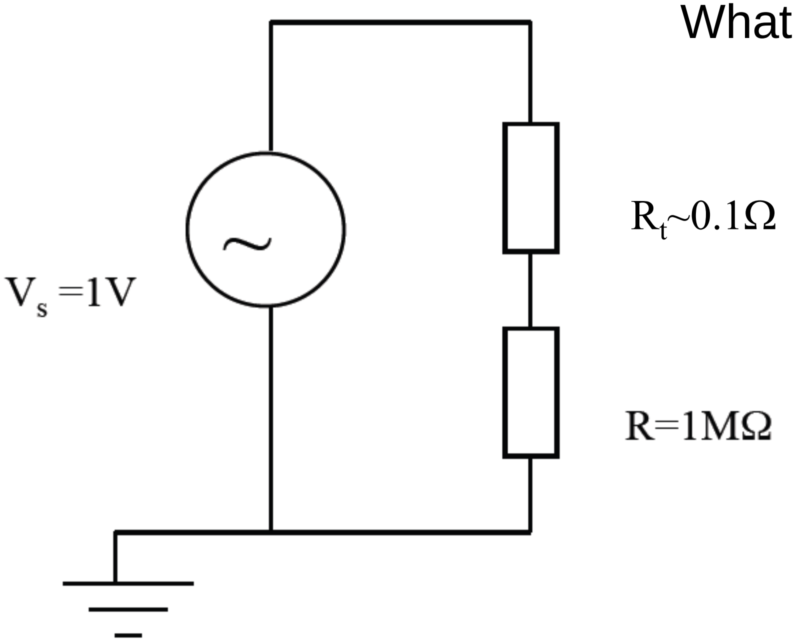
ICARUS collaboration, arxiv: 1208.2629v2 (sept. 2012)

# Example




What is the voltage across the 0.1Ω resistor?

We expect the voltage to be ~0.1μV

Johnson noise: $V_{noise}\left(\mathrm{RMS}\right) = \sqrt{4k_B TRB}$

For T=300K, R~1MΩ (resistance in circuit), and B=20MHz (e.g. lab scope);

$V_{noise}$(RMS)~0.5mV!

However, the noise will be distributed across *all frequencies* (wideband) whereas the signal ($V_s$) is at a *specific frequency*

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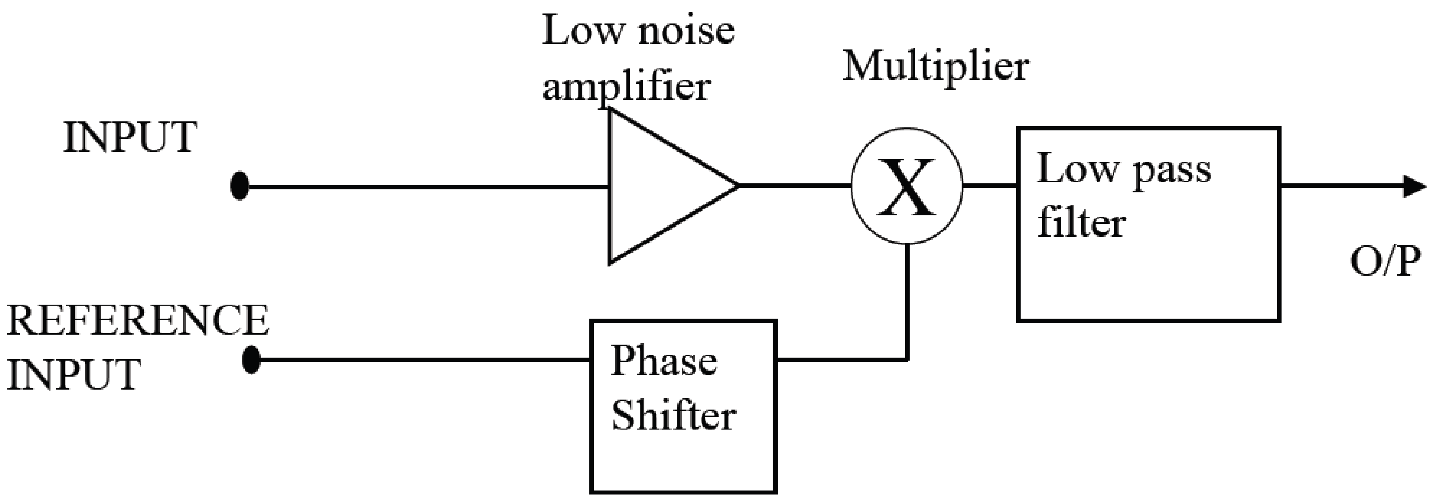
# LIA: Key components




1. A low noise amplifier
2. A phase shifter
3. A multiplier
4. A low pass filter
5. An output display (voltmeter)

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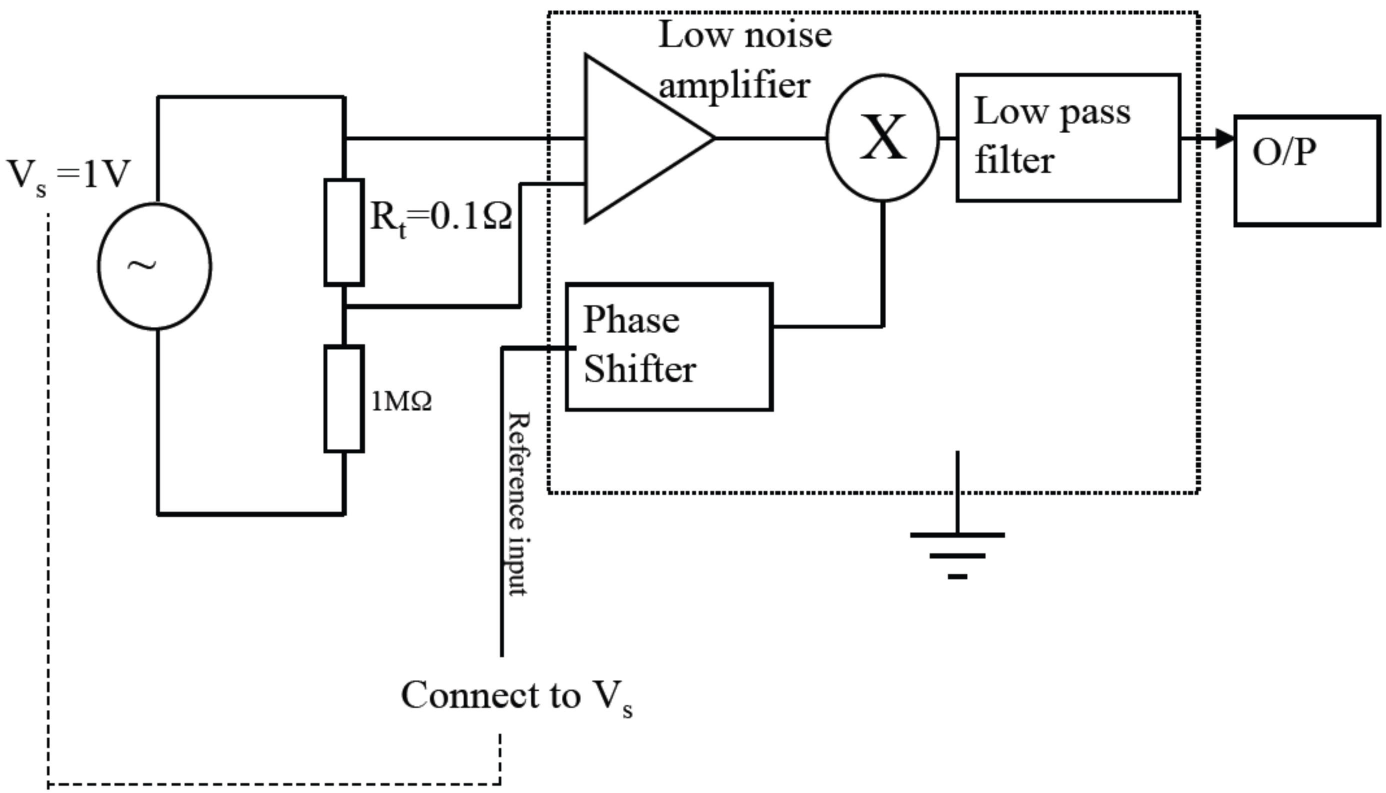
# LIA in a circuit

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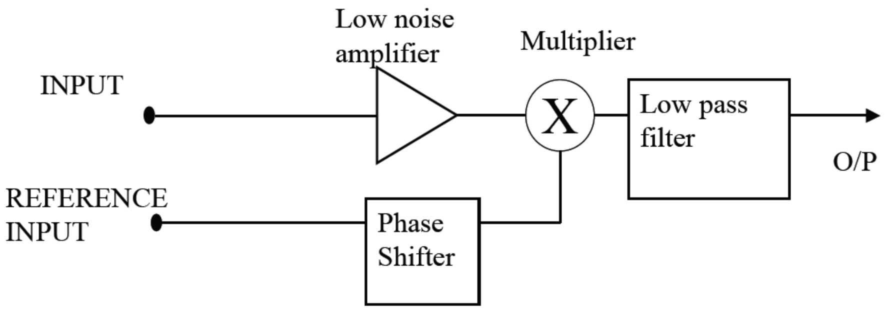
# Measurement procedure




Basic method for lock-in detection involves the following steps:

1. Generate a known AC reference signal (e.g. from a signal generator)
2. Modulate the measurement with this signal to generate the input signal to be measured (e.g. AC voltage across 0.1Ω resistor)
3. Amplify the noisy input voltage signal
4. Multiply the amplified input signal by the original reference signal
5. Pass the resultant multiplied signal through a low-pass filter and measure the output voltage signal – oscilloscope (DVM, chart recorder…)
6. Adjust the phase shifter such that the output voltage signal is maximised: there may be a phase shift between your measured signal and reference, e.g. LCR circuits
   – you can measure the phase-shifter separately using the sig-gen and oscilloscope to determine the phase-shift!

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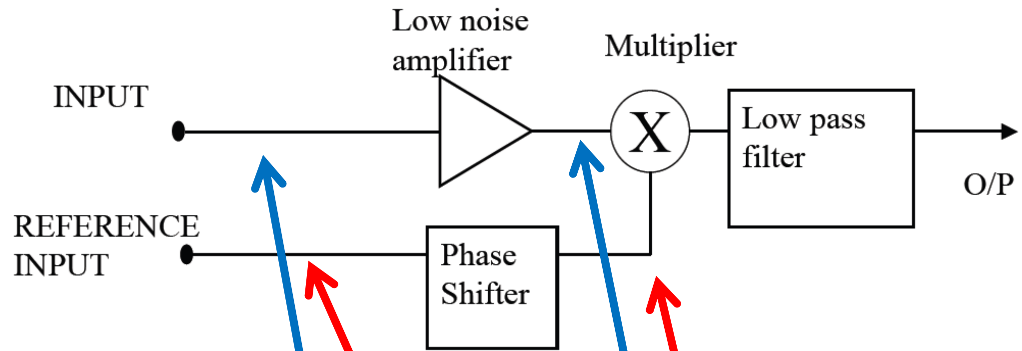
# Analysis




Let the reference signal be $V_{ref}\cos(\omega t)$

After the phase shifter this will then be $V_{ref}\cos(\omega t+\phi)$

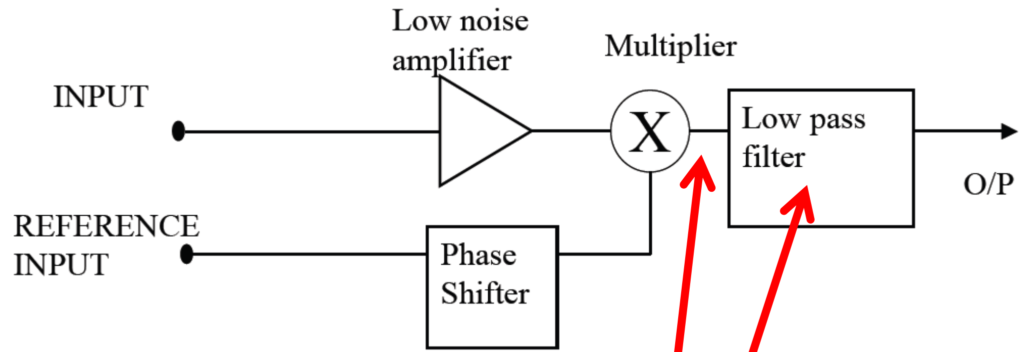
$V_{sig}$ does *not* have to be DC; it could be time-varying provided it has components only at frequencies which are small compared with carrier frequency, ω

If the signal to be detected is $V_{sig}\cos(\omega t)$

Then after amplifying this is $AV_{sig}\cos(\omega t+\phi_A)$

where *A* is the amplifier gain and $\varphi_A$ is the phase-shift induced by the amplifier (at frequency ω): both properties of the amplifier that you can design and/or measure

# Analysis (2)




The output of the multiplier is then $AV_{sig}\cos(\omega t+\phi_A)V_{ref}\cos(\omega t+\phi)$

Using the trig. identity $\cos(a+b)+\cos(a-b)=2\cos a\cos b$

this becomes $$\frac{AV_{sig}V_{ref}}{2}\left[\cos(2\omega t+\phi+\phi_A)+\cos(\phi_A-\phi)\right]$$

**This high-frequency (2ω) term is removed by the low-pass filter**

The *low-pass filter* should be designed with a corner frequency such as to *pass* any time-varying component of $V_{sig}$.

The final output is $$\frac{AV_{sig}V_{ref}}{2}\cos(\phi_A-\phi)$$

The phase term is maximized by adjusting the phase shifter so $\varphi_A=\varphi$. Since $A$ and $V_{ref}$ are known, so is $V_{sig}$

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# What about the noise component?

As before, the reference signal after the phase-shifter is $V_{ref}\cos(\omega t+\phi)$

If the input ***noise signal*** is $V_{noise}\cos(\omega_{noise}t)$

Remember: signal+noise must not saturate the amplifier!

After amplification this becomes $AV_{noise}\cos(\omega_{noise}t+\phi_A)$

Multiplying these and using the same trig identity as before gives the output of the multiplier as

$$\frac{AV_{noise}V_{ref}}{2}\left[\cos(\omega_{noise}t+\omega t+\phi+\phi_A)+\cos(\omega_{noise}t-\omega t+\phi_A-\phi)\right]$$

Now both of these terms are **AC**, and so are **removed by the low-pass filter!**

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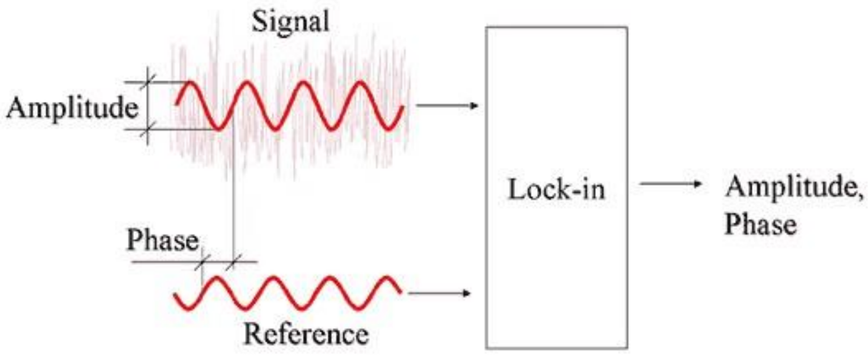
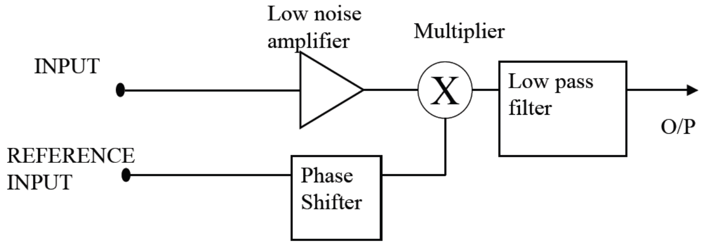
Note: signals for which $|(\omega_{noise}-\omega)|$ is less than the corner freq of the filter (which you design and can measure) will *not* be removed and *will* be measured

# Building a LIA




Key points:

- Input signal + noise must not saturate the output of the amplifier: need to know the amplifier gain and phase shift at reference frequency




- Low-pass filter must remove signal at reference frequency, without removing any lower frequency time-varying components of the input signal
- Output can be displayed on DSO – ensure suitable timebase and scale are set in order to record the output signal clearly
- Output signal amplitude should be maximised by adjusting phase shifter: phase shift between reference and amplifier output at reference frequency can then be measured separately

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# Benefits of lock-in detection

In principle, a similar effect to that of the LIA could be achieved with a very narrow 'band-pass' filter. However lock-in detection has the following advantages over a conventional filter circuit:

1. The circuit is "locked" automatically to the reference frequency: if the modulation frequency drifts (which it will) the detection circuit still works

2. Because it selects for phase as well as frequency, it offers better noise rejection than a band-pass filter of the same bandwidth

3. It is MUCH easier to build a relatively imprecise low-pass filter than a precise band-pass filter.

# Drawbacks

1. The output is a voltage representing the instantaneous magnitude of the largest frequency component common to both the signal and the reference – the actual waveform input into the LIA is lost

2. There is a trade off between bandwidth (determined by low-pass filter corner frequency) and response time
   - A low corner frequency on the LP filter gives a very narrow bandwidth and good noise rejection, but the output responds more slowly to changes in input amplitude
   - Conversely, a higher corner frequency allows more noise (where $|(\omega_{noise}-\omega)|$ is less than the corner frequency), but responds more quickly to changes in input amplitude

3. Comparatively expensive – commercial LIAs cost upwards of several £1000s: but you will design and build your own!

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# Summary

- Sources of noise in analog systems

- Lock-in (phase-sensitive) detection
  - Concept
  - Circuit and measurement procedure
  - Signal and noise analysis

You should now know everything that you need for your final electronics practical

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