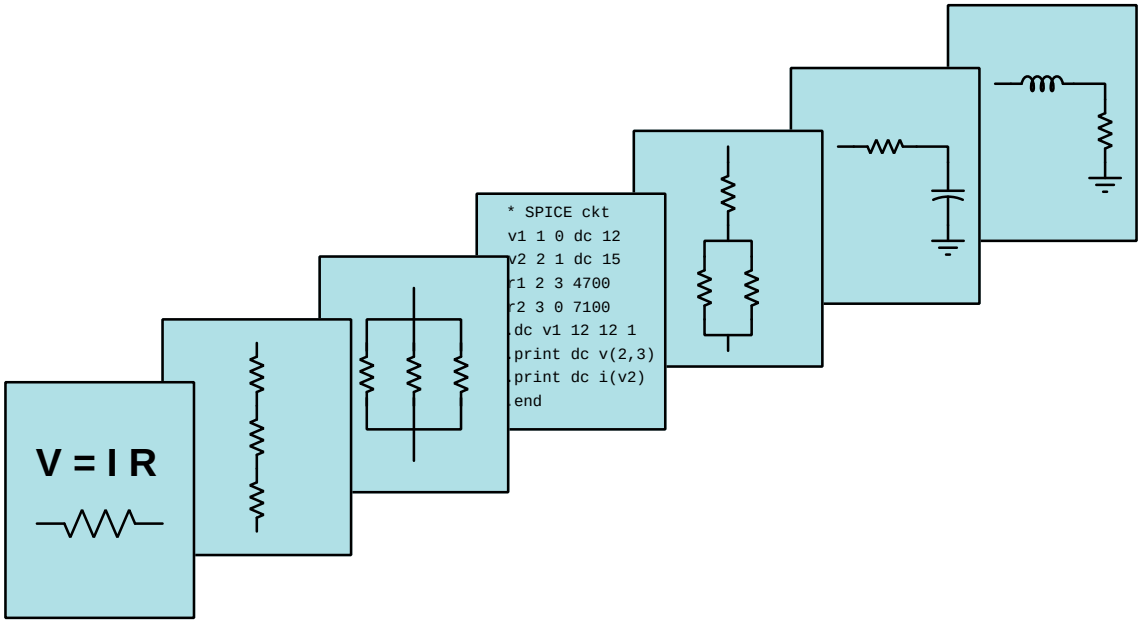
Modular Electronics Learning (ModEL) project



Antenna Feed Systems

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Contents

1 Introduction **3**
- 1.1 Recommendations for students . . . 3
- 1.2 Challenging concepts related to antenna feed systems . . . 5
- 1.3 Recommendations for instructors . . . 6

2 Case Tutorial **7**
- 2.1 Example: cable loss decibel calculations . . . 8
- 2.2 Example: HA8DU model DU-1500-T tuning unit . . . 9

3 Tutorial **13**
- 3.1 Antenna feed systems . . . 14
- 3.2 Antennas as sources and loads . . . 15
- 3.3 Feedlines . . . 18
- 3.4 Excessive standing wave ratio . . . 22
- 3.5 Antenna impedance matching . . . 24
- 3.6 Transceiver impedance matching . . . 29
- 3.7 Surge suppression and grounding . . . 31
- 3.8 Baluns and ununs . . . 35

4 Derivations and Technical References **41**
- 4.1 Decibels . . . 42
- 4.2 LC impedance-transformation networks . . . 52
- 4.3 Smith charts . . . 57
- 4.4 The Poynting vector . . . 66
- 4.5 Maxwell's equations of electromagnetism . . . 70
  - 4.5.1 Gauss's Law of electric fields . . . 70
  - 4.5.2 Gauss's Law of magnetic fields . . . 70
  - 4.5.3 Faraday's Law of electromagnetic induction, extended . . . 71
  - 4.5.4 Ampère's Circuital Law, extended . . . 71
  - 4.5.5 Proof of electromagnetic waves . . . 72
- 4.6 Common coaxial cable types . . . 74

5 Animations **75**
5.1 Animation of a standing wave with full reflection . . . 76
5.2 Animation of a standing wave with 50% reflection . . . 166

6 Questions **257**
6.1 Conceptual reasoning . . . 261
6.1.1 Reading outline and reflections . . . 262
6.1.2 Foundational concepts . . . 263
6.1.3 Optimum standing wave ratio . . . 266
6.1.4 Adjusting twin-lead impedance . . . 266
6.1.5 Ultimate Transmatch . . . 267
6.2 Quantitative reasoning . . . 268
6.2.1 Miscellaneous physical constants . . . 269
6.2.2 Introduction to spreadsheets . . . 270
6.2.3 Proper line termination . . . 273
6.2.4 Transformer impedance ratios . . . 273
6.2.5 Matching section . . . 273
6.2.6 Matching section calculator program . . . 274
6.3 Diagnostic reasoning . . . 275
6.3.1 Improperly-installed lightning arrestors . . . 276
6.3.2 Partially shorted transformer winding . . . 277

A Problem-Solving Strategies **279**

B Instructional philosophy **281**
B.1 First principles of learning . . . 282
B.2 Proven strategies for instructors . . . 283
B.3 Proven strategies for students . . . 285
B.4 Design of these learning modules . . . 286

C Tools used **289**

D Creative Commons License **293**

E References **301**

F Version history **303**

Index **305**

Chapter 1

Introduction

1.1 Recommendations for students

Components connecting an antenna to either a transmitter or receiver are collectively known as the *feed system* for a radio. This includes the cabling conveying the RF energy as well as any networks of components designed to match impedance values of disparate components.

Important concepts related to antenna feed systems include **transmission lines**, **impedance**, **reflected signals**, **standing waves**, **inductance**, **capacitance**, **transformers**, **Maximum Power Transfer Theorem**, the effects of **opens** versus **shorts**, **sources** versus **loads**, **Ohm's Law**, **standing wave ratio**, **balanced** versus **unbalanced** voltages, **transients**, and the **skin effect**.

Here are some good questions to ask of yourself while studying this subject:

- How might an experiment be designed and conducted to test the standing wave ratio for an antenna system? What hypothesis (i.e. prediction) might you pose for that experiment, and what result(s) would either support or disprove that hypothesis?
- How is it possible for an antenna, even if it possesses no resistance in its metallic components, may still act as a dissipative load?
- What factors affect the characteristic impedance of any cable?
- Under what conditions may standing waves exist along a cable?
- What does it mean to properly "terminate" a transmission line?
- Why must a feedline be impedance-matched to its connected antenna?
- Why must a feedline be impedance-matched to its connected transmitter or receiver?
- What consequences may result from improper impedance matching in an antenna feed system?
- How may we match inherently unmatched components in an antenna feed system?

- What is the purpose of a "dummy load" and when might one be used?
- What are some of the different types of feedlines used to connect an antenna to an RF amplifier?
- Which types of antenna are inherently balanced in design?
- Which types of antenna are inherently unbalanced in design?
- What causes transient surges in antenna feed systems?
- How are transients mitigated in antenna feed systems?
- What is "standing wave ratio" (SWR), and why is it important in an antenna feed system?

1.2 Challenging concepts related to antenna feed systems

The following list cites concepts related to this module's topic that are easily misunderstood, along with suggestions for properly understanding them:

- **Parasitic effects** – phenomena such as resistance, capacitance, and inductance don't just exist where we want them to, but in fact always exist everywhere they can. All conductors (except for superconductors) have some amount of resistance, all conductors separated by an insulating gap exhibit capacitance, and all conductors possess inductance by virtue of their ability to produce a magnetic field with the passage of current. Often these "parasitic" effects are small enough to ignore, but in some applications such as radio circuitry their presence is in fact absolutely necessary for the system to work at all!

- **Balanced versus Unbalanced signals** – voltage can only exist between two points, and so any voltage-based signal may either be referenced to ground (unbalanced, or single-ended) or expressed between two ungrounded points (balanced, or differential).

- **Decibels** – "decibels" are an attempt to express power ratios (i.e. power gains or attenuation factors) logarithmically rather than linearly, and as such they tend to generate confusion for students less familiar (or unfamiliar) with exponential and logarithmic functions.

- **Maxwell's equations** – the existence of electric and magnetic fields within empty space, with no conductors nearby, was a discovery made by James Clerk Maxwell in the late 1800's, and is as nonintuitive today as it was then. RF systems with their extremely high frequencies manifest effects related to detached electric and magnetic fields that are all but undetectable in lower-frequency systems.

1.3 Recommendations for instructors

This section lists realistic student learning outcomes supported by the content of the module as well as suggested means of assessing (measuring) student learning. The outcomes state what learners should be able to do, and the assessments are specific challenges to prove students have learned.

- **Outcome** – Demonstrate effective technical reading and writing

  Assessment – Students present their outlines of this module's instructional chapters (e.g. Case Tutorial, Tutorial, Historical References, etc.) ideally as an entry to a larger Journal document chronicling their learning. These outlines should exhibit good-faith effort at summarizing major concepts explained in the text.

  Assessment – Students present their "Conceptual Toolbox" Theory Journal entries listing important concepts applied in the Tutorial text(s). A "Conceptual Toolbox" serves as inspiration when solving problems, each concept suggesting a potential problem-solving action. Challenge students to collaboratively generate a Conceptual Toolbox for the day's topic during the class session and then use it when solving problems together, thus fostering the habit of reasoning from principles rather than recalling procedures!

- **Outcome** – Sketch proper connections for balanced and unbalanced antennas to connect to a transmitter

  Assessment – Identify where a given type of antenna is "blind" to incoming signals; e.g. pose problems in the form of the "Ultimate Transmatch" Conceptual Reasoning question.

- **Outcome** – Calculate parameters for impedance-matching networks

  Assessment – Determine proper number of turns for an impedance-matching transformer; e.g. pose problems in the form of the "Transformer impedance ratios" Quantitative Reasoning question.

  Assessment – Determine proper parameters for a quarter-wave matching section; e.g. pose problems in the form of the "Matching section" Quantitative Reasoning question.

- **Outcome** – Independent research

  Assessment – Read and summarize in your own words reliable documents on antenna feed systems. Publications by the American Radio Relay League (ARRL) are highly recommended!

  Assessment – Locate antenna feed system component datasheets and properly interpret some of the information contained in those documents including impedance, RF connector types, physical dimensions, power rating, etc.

Chapter 2

Case Tutorial

The idea behind a *Case Tutorial* is to explore new concepts by way of example. In this chapter you will read less presentation of theory compared to other Tutorial chapters, but by close observation and comparison of the given examples be able to discern patterns and principles much the same way as a scientific experimenter. Hopefully you will find these cases illuminating, and a good supplement to text-based tutorials.

These examples also serve well as challenges following your reading of the other Tutorial(s) in this module – can you explain *why* the circuits behave as they do?

2.1 Example: cable loss decibel calculations

If a radio transmitter sends 15 Watts of power into a coaxial cable having a loss rating of −0.16 dB per meter, and the cable is 20 meters in length, the power available at the far end of the cable must be **7.1795 Watts**.

If an RF signal source sends 10 mW into one end of a 5-meter cable and the other end of the cable outputs 8 mW of signal power, the cable must have a loss rating of **−0.194 dB per meter**.

An RF signal of 2 Watts exits a cable 3 meters in length having a loss rating of −0.14 dB per meter. The amount of power being input to this cable must be **2.203 Watts**.

An RF signal of 15 Watts enters one end of a cable having a loss rating of −0.21 dB per foot, and an RF signal of 10 Watts exits the other end of that same cable. The cable's length must be **8.38530 feet**.

A 50-Watt radio transmitter connected to a 12-foot cable having a loss rating of 0.041 dB/foot terminates at a lightning arrestor with a loss rating of 0.5 dB, and finally to an antenna. The amount of power received by this antenna will be **39.7896 Watts**.

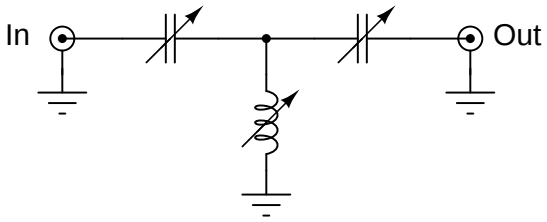
2.2 Example: HA8DU model DU-1500-T tuning unit

The model DU-1500-T antenna tuning unit manufactured by HA8DU is a "full legal limit" tuner in that it is rated at the full legal power output limit for amateur radio service of 1500 Watts as specified by the FCC in the United States. It is a "pi" topology circuit consisting of a series input capacitor, a parallel inductor, and a series output capacitor. Both capacitors are infinitely variable while the inductor is tapped and selected by a multi-position switch.

This unit's rear panel features a single SO-259 "UHF" connector labeled "Input 50 Ω" for attachment to the transceiver unit, along with two outputs to antennas ("Coax 1" and "Coax 2") as well as another SO-259 connector labeled "Bypass" which often connects to a 50 Ohm dummy load for testing. For balanced feedline operation, two metal studs with wing-nuts serve as connection posts, while a jumper wire connecting a third post to the center conductor of one of the "Coax" outputs directs the unbalanced output of the tuner to an internal 4:1 voltage balun:

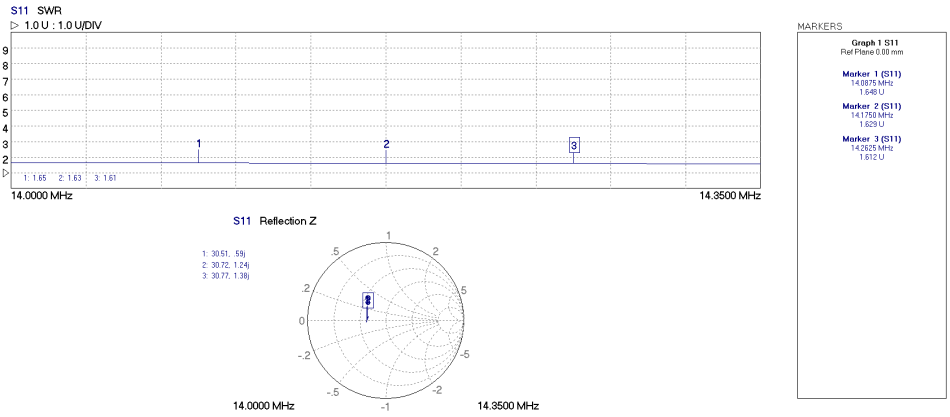
A photograph of the unit's internal componentry clearly shows the two variable capacitors as well as a pair of inductors[1] with taps connecting to a rotary selector switch. This is a less expensive design than a roller-contact style variable inductor:

A very simplified schematic diagram shows the basic topology of the matching network:

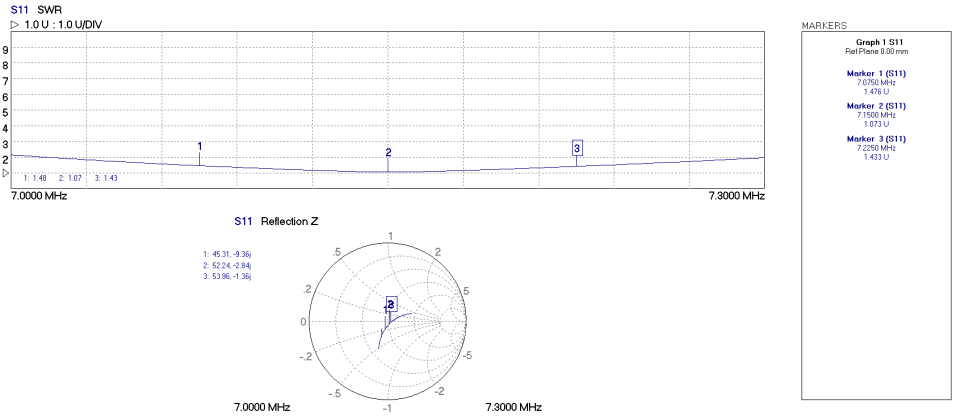


[1] Note how these inductors are mounted perpendicular to each other, to minimize coupling between them.

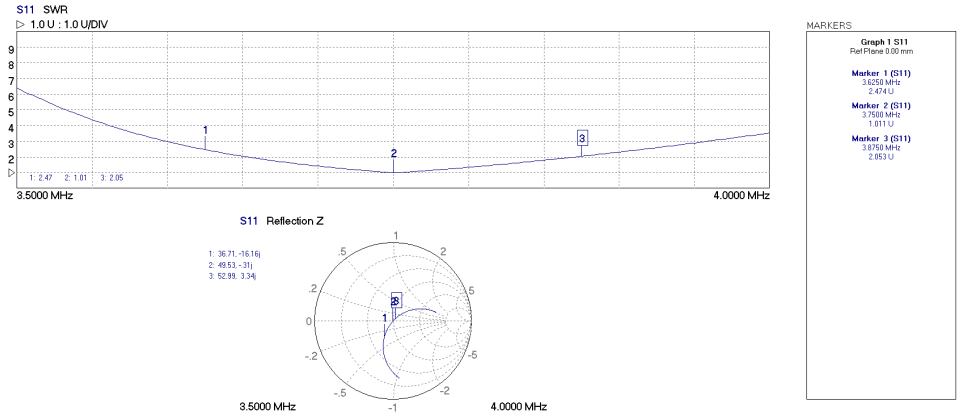
Testing this unit with a 17 Ohm dummy load simulating an antenna, and operating over a frequency range of 14 to 14.35 MHz which is the 20 meter amateur radio band, we see the following results shown by a VNA plotting both standing-wave ratio (SWR) and complex impedance on a Smith Chart:



Testing this unit again with a 17 Ohm dummy load simulating an antenna, this time operating over a frequency range of 7 to 7.3 MHz which is the 40 meter amateur radio band, we see the following results shown by a VNA plotting both standing-wave ratio (SWR) and complex impedance on a Smith Chart:



Testing this unit once again with a 17 Ohm dummy load simulating an antenna, and operating over a frequency range of 3.5 to 4 MHz which is the 80 meter amateur radio band, we see the following results shown by a VNA plotting both standing-wave ratio (SWR) and complex impedance on a Smith Chart:



The more pronounced curvature of the SWR plot as we progress from 20 meters to 40 meters to 80 meters is due to the fact that the width of each of these amateur radio service bands is a larger percentage of the center frequency value. For example, the 80 meter band that runs from 3.5 MHz to 4 MHz has a total bandwidth of 0.5 MHz which is 13.33 percent of the center frequency for that band (3.75 MHz). By contrast, the 0.3 MHz bandwidth of the 40 meter band is only 4.2 percent of that band's center frequency, and the 0.35 MHz bandwidth of the 20 meter band is only 2.47 percent of that band's center frequency. In other words, the 80 meter band encompasses a proportionately larger frequency range than the 40 meter band, and the 40 meter band more than the 20 meter band.

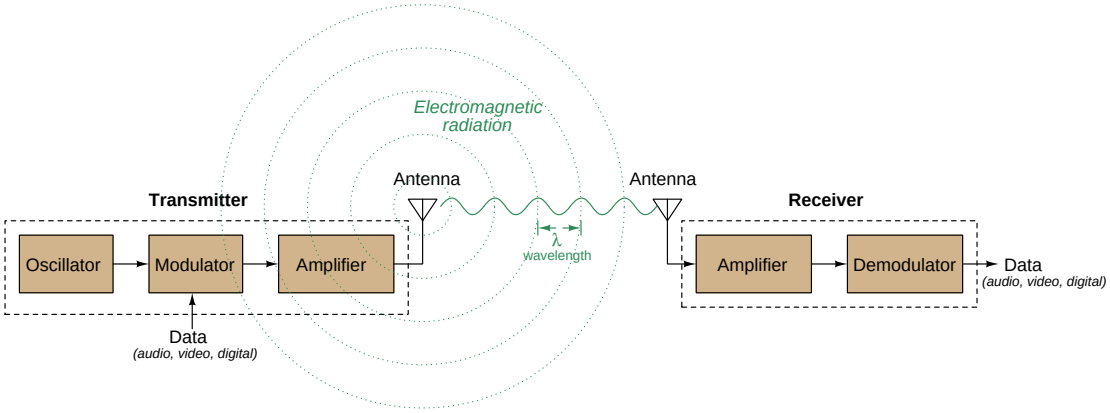
With this fact in mind, we can tell that adjusting a reactive tuning unit such as this will involve more work for the radio operator when optimizing performance across the 80 meter band (i.e. will require multiple adjustments to keep SWR low no matter what exact frequency is being worked) than it will either the 40 meter or 20 meter bands. The SWR plot is so flat for the 20 meter band that once adjusted for any point on that band the tuner probably won't have to be adjusted at all for any other frequency within that band!

Chapter 3

Tutorial

3.1 Antenna feed systems

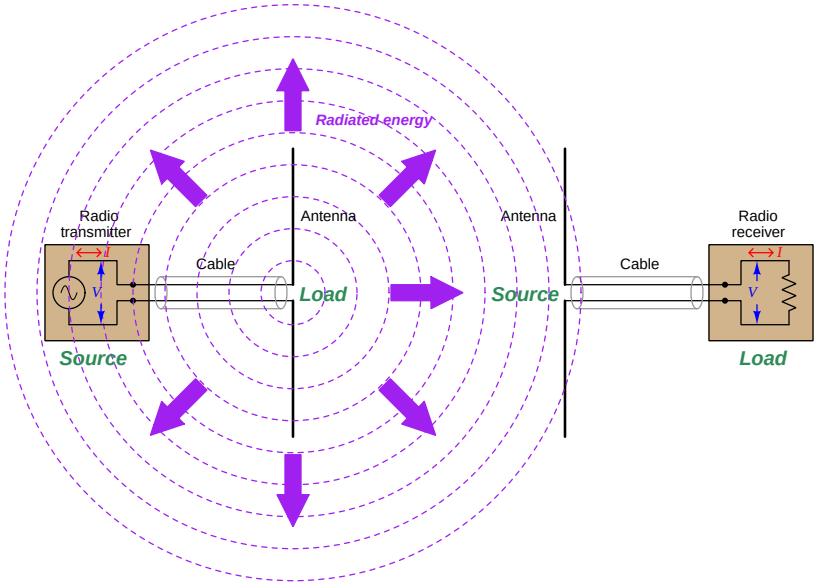
At its most elemental, radio communication is a fairly simple phenomenon: we connect a high-frequency AC electrical to a metallic structure called an *antenna* to translate that electrical energy into electromagnetic *waves* of mutually-sustaining electric and magnetic fields radiating out into the surrounding space. By *modulating* that high-frequency signal with information such as speech, the radiated waves function as a carrier of that information to remote locations where it may be intercepted by other antenna structures, translated into electrical signals by those antennae, *demodulated* to recover the information, and presented to a receiving circuit or person for practical use:



Perhaps the least impressive portion of any radio communication system is the connection between the antenna and transmitter/receiver amplifier. On the block diagram shown above, it is nothing but a short, angled line connecting each amplifier to its antenna. However, this does not mean its function is trivial. Quite to the contrary, the wiring and components necessary to properly couple a transmitter or receiver to its antenna comprise a subsystem in its own right, worthy of study. This tutorial explores some of the important concepts related to the components lying in between a radio unit and its antenna, collectively known as an *antenna feed system*.

3.2 Antennas as sources and loads

An *antenna* is nothing more than one or more metallic conductors exploiting the phenomena of parasitic capacitance and inductance to either generate or intercept electromagnetic fields. Energize an antenna with AC of the proper frequency and it radiates electromagnetic energy into space; subject an antenna to electromagnetic waves and it experiences induced voltages and currents from those waves:

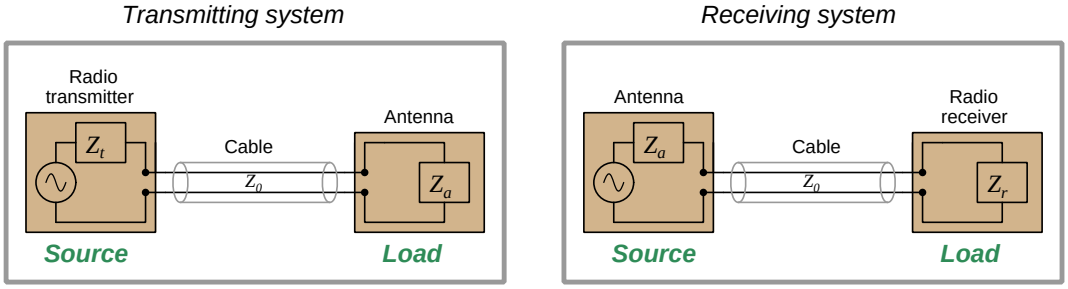


Normally we think of capacitance and inductance as *reactive* phenomena, capable of absorbing and releasing energy (in electric and magnetic fields, respectively) but not dissipating energy. However, in the case of a radio transmitting antenna energy definitely leaves the transmitter circuit in the form of electromagnetic radiation never to return. This means an antenna acts as a *load* to the transmitter's *source*. On the receiving end of the radio link, the antenna's natural capacitance and inductance act to intercept the electromagnetic fields to produce voltage and current, and as this electrical energy is converted into other forms inside the receiver we see the receiving antenna functions as a *source* to the receiver's *load*.

Just as the parasitic capacitance and inductance of the conductors comprising a transmission line imposes a definite-impedance load on any transient signal impressed at one end, an antenna similarly exhibits a definite impedance value to any energizing signal. When operated at resonance, this antenna impedance is purely resistive[1] rather than being either capacitive or inductive, and its value depends on the form of antenna as well as its surroundings. This characteristic impedance exists whether the antenna acts as a load (to a transmitter) or as a source (to a receiver), and for an ideal dipole antenna will be approximately 73 Ohms. It is referred to as *radiation resistance* because the ratio between voltage and current ($R = \frac{V}{I}$) is a function of the electromagnetic radiation.

[1] Similarly, an infinitely-long transmission line also behaves like a resistor from the perspective of the energizing source because the energy absorbed by it is never returned.

It is helpful to model the essential components of a radio system as Thévenin equivalent networks, each source containing an AC voltage element and series-connected impedance, and each load consisting solely of an impedance. Any conductors joining the two functions as a transmission line, possessing its own characteristic (or "surge") impedance, Z_0 being a function of conductor spacing and geometry:



In accordance with the Maximum Power Transfer Theorem, load impedance must match source impedance in order to optimize energy transfer from source to load. This means Z_a should equal Z_t for a transmitting system, and that Z_r should equal Z_a for a receiving system. Furthermore, load impedance and transmission line impedance values should also match in order to avoid *reflected signals* within the cable. Therefore, the ideal transmitting system will have $Z_t = Z_0 = Z_a$ and the ideal receiving system will have $Z_a = Z_0 = Z_r$.

Such perfect impedance matching is rarely the case in real radio systems. While transmitter and receiver circuits may be designed to present almost any amount of impedance to the antenna, antenna radiation resistance is fundamentally defined by the structure of the antenna, that structure often being dictated by limitations of the site as well as by the desired signal gain and directionality of the antenna. Transmission line impedance is also constrained, in this case by the geometry of the conductors (primarily, their spacing from each other) and by the insulating media separating them. It becomes necessary in many cases, therefore, to insert other components between the antenna and the transmitter/receiver in order to make disparate impedances compatible with each other for optimum performance.

It is worth noting that radio transmitters are generally tested for proper operation with a suitable load resistor (i.e. a load having a resistance value equal to the antenna's radiation resistance) connected in lieu of an antenna. By doing this, the transmitter's performance may be thoroughly investigated under the same loading conditions that an antenna would ordinarily provide without actually broadcasting any electromagnetic radiation. Such "dummy load" testing is especially important if the transmitter has not yet been adjusted for proper frequency or purity of spectrum, because actually broadcasting radio-frequency energy into the world with a poorly-adjusted transmitter will likely accomplish nothing except produce interference!

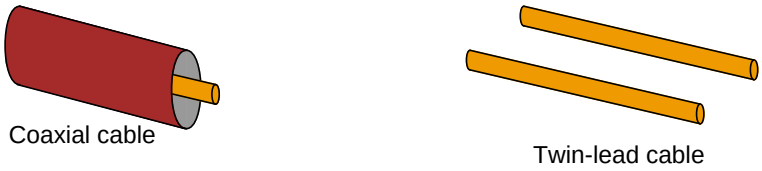
The following photograph shows a 50 Ohm resistor specifically designed for transmitter testing, this one with a power rating of 150 Watts maximum:

One should *never* operate a radio transmitter without some form of load connected to its output, whether that be a proper antenna or a "dummy" load. Failure to do so may actually cause damage to the transmitter's internal circuitry, especially in the case of high-powered radio transmitters! Even Citizen's Band (CB) radio transceivers rated at just 5 Watts of output power come with warnings not to transmit without the output connected to a proper load.

3.3 Feedlines

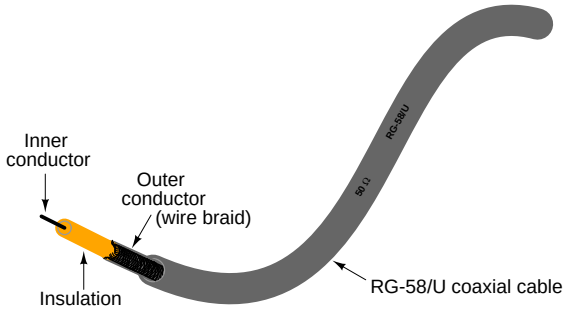
In discussing the conductors connecting an antenna to its transmitter or receiver unit, we have so far referred to this assembly as a *transmission line*, primarily to think of it in terms of exhibiting a characteristic impedance to any conveyed signals. In radio practice it is common to refer to it as a *feedline* due to its function of "feeding" radio-frequency (RF) electrical energy from transmitter to antenna or from antenna to receiver.

Feedlines take several different forms, some common designs being *coaxial* and *twin-lead*. A coaxial feedline consists of a wire conductor surrounded by a metallic tube (or foil or braid in the case of flexible coaxial cable), the wire and its surrounding sheath sharing the same centerline (i.e. co-axial to one another). A twin-lead feedline is a pair of parallel wires separated[2] either by periodically-spaced insulators or by a ribbon of plastic insulation.



Coaxial cable exhibits excellent electrostatic *shielding* if the outer conductor is bonded to Earth ground at one end, minimizing radiation losses along the cable. Twin-lead cable by comparison radiates some electromagnetic energy when used as an RF feedline. Coaxial cable is also easier to lay around corners and through walls than twin-lead. However, flexible coaxial cable suffers greater thermal losses than twin-lead, due to dielectric heating of the solid (usually plastic) insulation separating the center and outer conductors.

An illustration showing flexible coaxial cable (type RG-58/U) appears below:



[2]The insulating separators used in twin-lead feedline give that style of feedline the popular name *ladder line*.

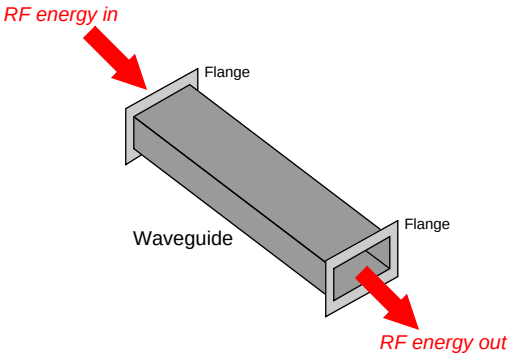
Rigid and *semi-rigid* coaxial feedline is popular for higher-powered transmitters, where the inner conductor is separated from the outer conductor by occasional spacers, with air (or another gas) functioning as the insulating medium over most of the line's length. The following photograph shows three runs of rigid copper coaxial feedline joined to two sections of semi-rigid coaxial feedline, used at a commercial AM transmitting station:

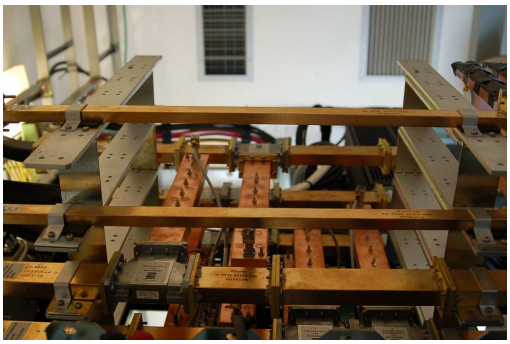
Note the white plastic tube connecting two of the rigid coaxial feedlines together. This plastic tube conveys dry, pressurized nitrogen gas from one line to the next, the purpose of this gas being to prevent atmospheric moisture from entering the interior of the feedline as well as to increase the line's dielectric strength (i.e. maximum operating voltage of the feedline).

Rigid coaxial feedline is essentially a specialized form of copper metal pipe, and as such requires special fittings to join sections together, to bend around corners, etc. It is expensive, but for high-power applications nothing else works quite as well. Semi-rigid coaxial cable represents a compromise both in cost and in performance between rigid and flexible coaxial feedline.

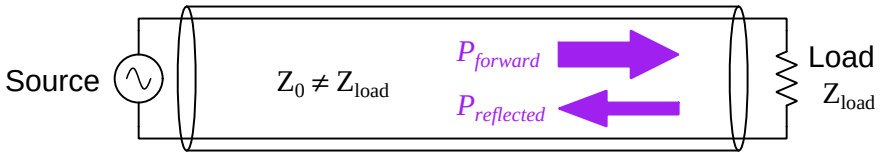
Since both of these coaxial cable types lack the solid plastic fill material used as insulation within flexible coaxial cable, they suffer far less power loss (due to dielectric heating of the plastic insulation by the high-frequency electric field) and are therefore able to convey greater amounts of power without overheating. Both rigid and semi-rigid coaxial cables are also much more dimensionally stable than flexible coaxial cable, making their electrical properties (e.g. characteristic impedance) more predictable as a result.

Another form of feedline called a *waveguide* is worth mentioning, but will not be discussed any further in this tutorial because it applies only to high-powered microwave RF systems which are sufficiently specialized to deserve their own tutorial. A waveguide is a hollow metal tube serving as a conduit for RF energy, much like a "pipe" for electromagnetic waves. Waveguides function only at extremely high frequency values, but enjoy the advantage of extremely low power loss due to either thermal effects (i.e. resistive or dielectric heating) or radiation. On the left is an illustration of a waveguide section, and on the right a photograph of a waveguide network connecting multiple microwave transceivers to antennas:

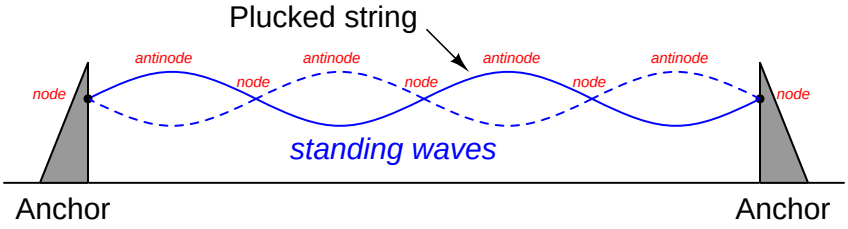




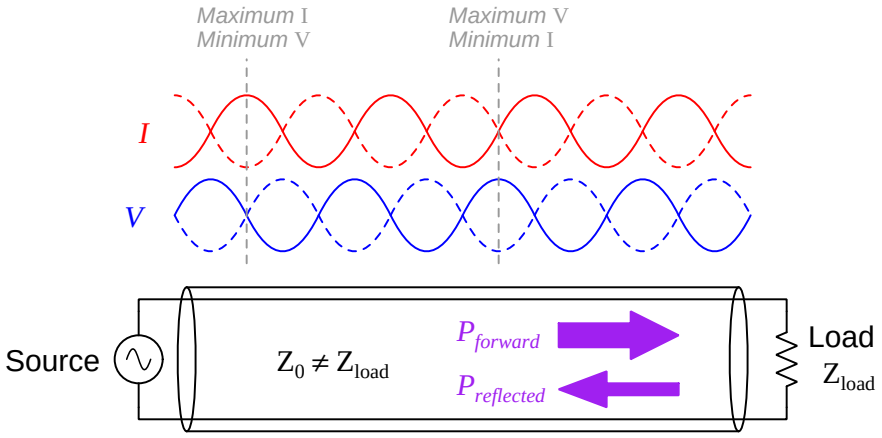
If any form of feedline connects to a load having a different impedance than the line itself, some of the energy traveling along the feedline toward the load will reflect back toward the source. We may express this as two different power values, *forward* power and *reflected* power:



As the reflected power wave constructively and destructively interferes with the forward power wave, *standing waves* emerge along the transmission line. These are oscillating regions of voltage and current that do not propagate along the line, but rather "stand" in place. As a result, some points along the line will experience greater AC voltage than others, and some points will experience greater AC current than others. This phenomenon has many mechanical equivalents, including the existence of standing waves in plucked musical instrument strings:



An example of how standing waves may[3] appear along a transmission line is shown below, for a line terminated in a mis-matched impedance value ($Z_{load} \neq Z_0$).



If the transmission line's termination is either an open or a short, the minimum values for voltage and current will reach zero[4] at their respective *node* locations. For less-extreme conditions of mismatch the node (minimum) and anti-node (maximum) points will have values for voltage and current that are closer to being equal to each other. In a perfectly-matched condition where there are no standing waves (i.e. a *flat* transmission line), voltage will be equal at all locations, as will current.

For any energized transmission line, the ratio between the maximum voltage and minimum voltage at different locations along the line is called the *Standing Wave Ratio*, or *SWR*. This happens to be the same ratio between maximum and minimum current values as well. An ideal (perfectly-matched, or "flat") transmission line will have an SWR equal to one, and any SWR value greater than one represents a mismatch between the line's characteristic impedance and the load.

[3] This particular example shows a transmission line several wavelengths' long.

[4] This is a *highly* non-intuitive conclusion of standing waves, that there may actually be points along an energized transmission line where zero voltage exists, and other points where zero current exists!

3.4 Excessive standing wave ratio

High SWR is undesirable because it represents ineffective transfer of energy from source to load, and it also results in greater energy dissipation (in the form of heat) along the transmission line, as well as the potential for greater losses within the source. In this way, a high SWR is analogous to a *low power factor* in an AC power circuit: a condition where the load is substantially reactive which results in energy being shuttled back and forth between source and load rather than flowing unidirectionally from source to load. In a radio transmitting system, excessive SWR may even damage the output stage of the transmitter or RF amplifier unit!

This is how operating a radio transmitter without a proper load connected to its output may cause damage: with the output open-circuited all the transmitter's power gets reflected back where it may manifest as high voltage. A suitable alternative for a proper antenna connected to a radio transmitter is, of course, a "dummy" load resistance ideally equal in value to the antenna's radiation resistance.

Causes of excessive SWR in a radio transmitter system include the following:

- Antenna radiation resistance poorly matched[5] to the feedline/transmitter
- Antenna length incorrect, skewing antenna feedpoint impedance to some abnormal value
- Poor connection to ground (e.g. for quarter-wave "monopole" antennas)
- Poor soil conductivity (e.g. for ground-mounted quarter-wave "monopole" antennas)
- Short-circuit in feedline or antenna
- Open-circuit in feedline or antenna, also loose connections
- Ground fault in feedline or antenna
- Fault in transmitter (causing its output impedance to be off-spec)

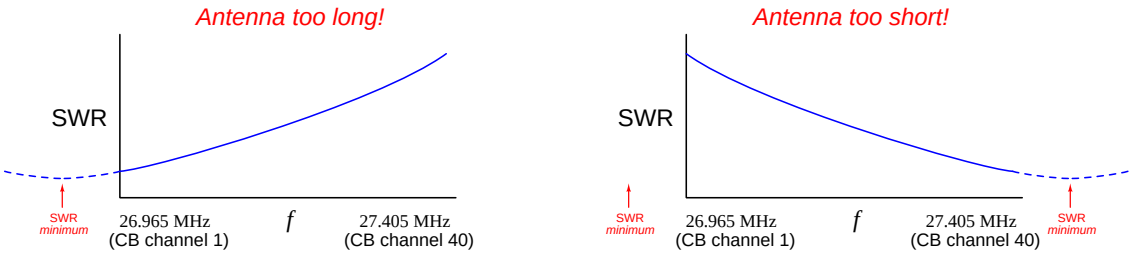
The first of these causes (antenna length) provides a good *thought experiment* for reviewing the phenomenon of resonance, which is the ideal condition for antenna operation. An antenna operating in a condition of resonance "appears" from the perspective of the radio transmitter to be a purely resistive load because its natural capacitive and inductive reactances perfectly cancel out at that frequency, the remaining resistance mostly comprised of the antenna's *radiation resistance* representing dissipation of energy into space in the form of radiated electromagnetic waves. Operated either above its resonant frequency or below, an antenna exhibits un-canceled reactance, all other factors remaining equal. If we imagine an antenna that is too short for the transmitter it's connected to, we know its resonant frequency will too high because a shorter length means a shorter resonant wavelength, which means it will approach resonance as the transmitter's frequency is increased. Conversely, we may imagine an antenna that is too long which means it will have a resonant frequency that is too low (longer resonant wavelength, resulting in reduced reactance as transmitter frequency decreases and approaches that point of resonance.

[5] An ideal half-wave dipole exhibits approximately 73 Ohms of resistive impedance at its proper (resonant) operating frequency, but certain parasitic factors such as close proximity to reflector and director elements as in the case of a Yagi style antenna may significantly skew that impedance value. In the case of Yagis it decreases antenna feedpoint impedance, in some cases from the bare dipole ideal of 73 Ohms down to as low as 10 Ohms!

For a well-installed antenna one of the simplest parameters to adjust in order to obtain a low SWR is the antenna elements' *lengths*. Quarter-wave monopole antennas may be constructed in such a way as to have adjustable length, and in such applications the antenna's length may be carefully varied in order to achieve the best SWR. Many radio transmitters have an SWR meter built in as a feature for antenna adjustment, as seen below in the close-up view of a Citizen's Band transceiver faceplate, where the upper-most scale of the analog meter face reads in SWR (unitless) as the unit outputs power to the antenna with the microphone's "talk" button depressed:

On a Citizen's Band transmitter, the "channel" number is proportional to frequency, with channel 1 being 26.965 MHz and channel 40 being 27.405 MHz. Thus, adjusting frequency on a CB radio to test for proper antenna length is as simple as adjusting the channel number while monitoring the SWR meter in "transmit" mode. For a well-adjusted antenna the SWR should dip to a minimum value at some channel frequency within the transceiver's adjustment range. If this minimum value lies outside that range (i.e. the minimum SWR occurs at one end or the other of the frequency range) then the antenna length needs to be adjusted.

A graphical analysis is helpful in determining whether a transmitting antenna is too long or too short based on SWR measurements taken at different transmitting frequencies. In this example we are assuming the frequency range of Citizen's Band (CB) radio, but the general principle applies to any radio transmitter having an adjustable output frequency:

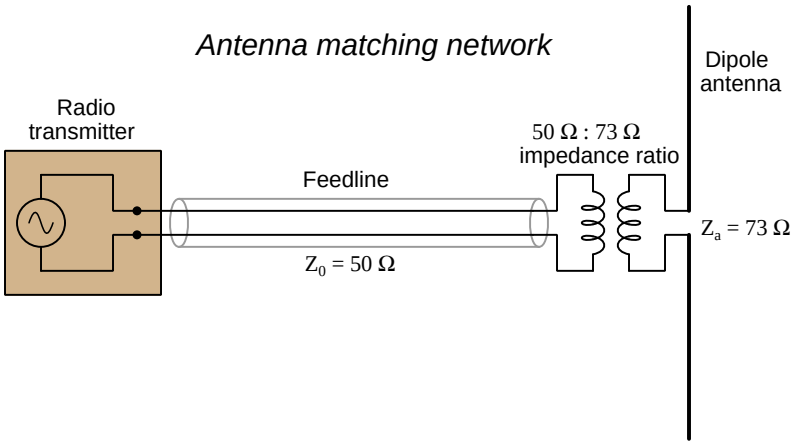


If the SWR keeps decreasing as frequency is decreased, it means the minimum SWR point must lie below the transmitter's lowest adjustable frequency, which in turn means the antenna is physically too long and muse be shortened. Conversely, if SWR always increases as frequency is increased, it means the minimum SWR lies above the transmitter's highest adjustable frequency, meaning the antenna is too short and must be lengthened.

3.5 Antenna impedance matching

Antenna impedance is often impractical to adjust. Transmission line impedance may be changed only by altering the physical dimensions of the conductors and their spacing along the entire length of the line. How then, may we ensure a good match between any given antenna and its feedline given these practical constraints? The answer in many cases is that we do not attempt to match these impedances, and simply live with an imperfect SWR (i.e. greater than one). For example, a 73 Ohm dipole antenna fed by a 75 Ohm feedline represents a very close impedance match. Even when fed by a 50 Ohm feedline, the mismatch between the line and a 73 Ohm antenna is probably acceptable for low-power operation.

In cases where a good impedance match is important for reasons of power efficiency and/or equipment safety, an *antenna coupling network* or *antenna matching network* may be used in-between the antenna and the feedline to transform the impedance values of each. Many types of matching networks exist, but they all achieve the same purpose as a *transformer* used to match impedances:

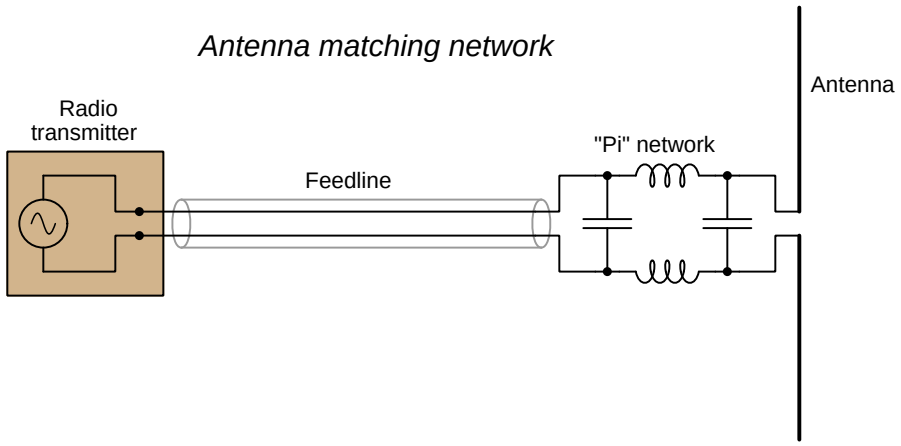


A transformer's impedance ratio is the square of its turns ratio:

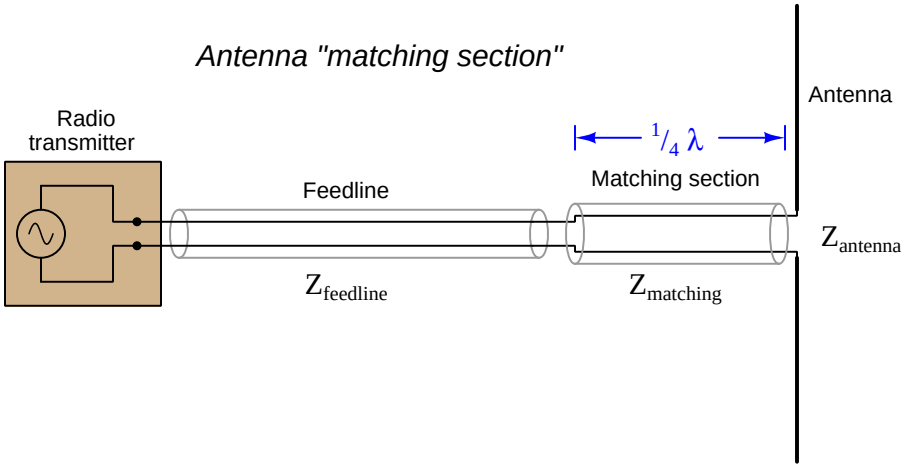
$$\frac{Z_p}{Z_s} = \left(\frac{N_p}{N_s}\right)^2 \qquad \frac{N_p}{N_s} = \sqrt{\frac{Z_p}{Z_s}}$$

For this particular example, the matching transformer's turns ratio must be $\sqrt{\frac{73}{50}}$, or 1.2083 to one. Since it is physically impossible to make a transformer winding with anything but a whole number of turns, we would need to find two whole-numbered turns values that together would make this 1.2083:1 ratio. For example, 121 turns on the antenna side and 100 turns on the feedline side would yield 1.21:1 which is quite close. If fewer turns were deemed advantageous (e.g. to reduce leakage inductance), we might make a transformer with 12 turns on one winding and 10 on the other, or 24:20, or 6:5, etc. to get a 1.2:1 ratio which is also quite close to the ideal turns ratio.

Many antenna couplers actually take the form of L-shaped or π-shaped L and C networks, which also serve to help filter out undesired harmonics from being transmitted by the antenna:



An even more interesting method of coupling an antenna to a feedline with differing impedance values uses a section of custom-made[6] transmission line exactly one-quarter wavelength long, the purpose of this *matching section* being to exploit the properties[7] of standing waves on a length of transmission line to transform impedance:



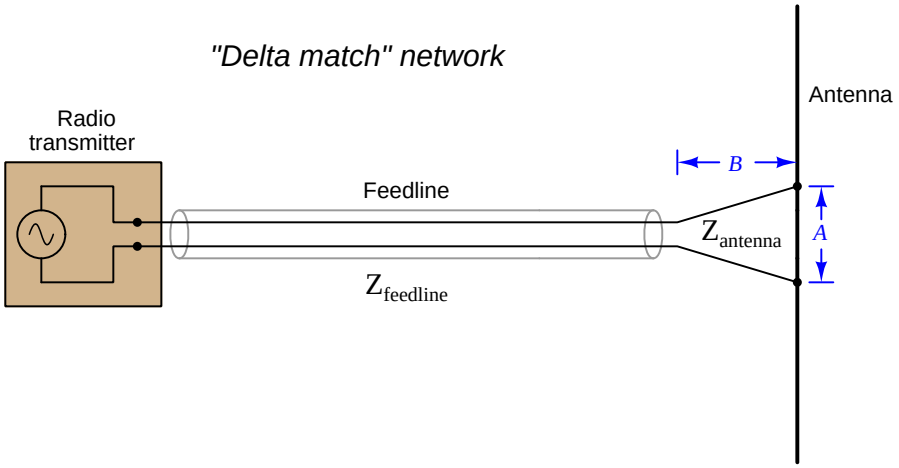
[6]The characteristic impedance of any two-conductor transmission line is a function of the conductors' spacing and the dielectric material separating them. For a twin-lead air-insulation matching section, controlling the spacing between conductors allows one to customize the impedance of that section rather easily.

[7]When the voltage and current waves "standing" along the length of an unmatched transmission line are out of phase, the effective impedance also varies at different points along the line. When $\frac{V}{I}$ is high, Z is high; when $\frac{V}{I}$ is low, Z is low. A transmission line of one-quarter wavelength operating with standing waves will exhibit high voltage and low current at one end, and low voltage and high current at the other. Thus, the quarter-wavelength section matches high impedance at one end with low impedance at the other.

The necessary characteristic impedance of the quarter-wavelength matching section must be equal to the square root of the product of the feedline and antenna impedance values:

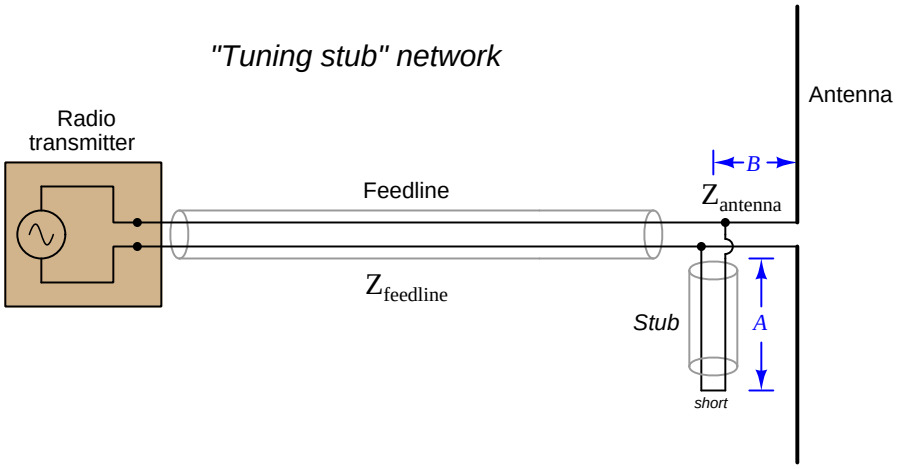
$$Z_{matching} = \sqrt{Z_{feedline} Z_{antenna}}$$

A technique similar to the matching section is something called a *delta match*, where the balanced feedline conductors splay out to connect to the dipole element some distance away from the center. Note that the dipole in this case is an continuous conductor with no separation in the middle:



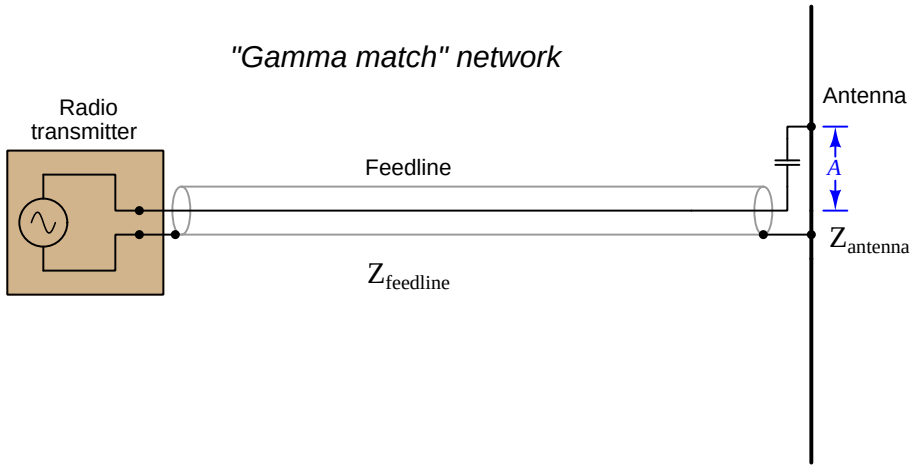
This is one of those cases prompting many a person to conclude in utter confusion that antenna theory is just magic: *how can this work at all if the dipole acts as a direct short to the feedline?* If the signal in question were DC rather than high-frequency AC, this system would indeed be nothing more than a direct short across the end of the feedline. However, it is good for us to reflect on the fact that antennas like transmission lines may be modeled as a collection of lumped L and C parameters, and are therefore capable of harboring different amounts of electrical potential and current at different points along their length. In the case of a half-wave dipole it resonates with potential antinodes at the tips and a voltage node at the center, and at the delta match's connection points there will be non-zero electrical potentials which means no short-circuit. In fact, the amount of impedance presented by the antenna varies with the dimensions A and B shown in this illustration, allowing the delta match system to provide an *adjustable* antenna impedance.

A related impedance-matching technique uses lengths of transmission lines called *stubs* connected in parallel with the feedline at some point near the antenna. The length of these stub cables and the distance between their connection to the feedline and the antenna itself are both parameters affecting the antenna's transformed impedance value. Shorted-end stubs are yet another cause for confusion when people familiar with DC circuits first encounter antenna systems, as the shorted stub cable certainly looks as though it would prevent excitation of the antenna:



That stub cable, however, having a length that is some significant fraction of the RF signal's wavelength, presents a non-shorted impedance to the feedline despite being shorted at its far end. That amount of impedance, and the corresponding effect it has on the antenna's apparent impedance where it connects to the feedline, depends on the physical dimensions A and B as well as on the characteristic impedance of the stub cable itself.

Yet another method of matching a feedline to a dipole antenna is the *gamma match*, which like the delta match strategy uses a continuous, unbroken dipole element. This is a popular method for impedance matching because it works well with unbalanced (grounded-shield) coaxial feedlines, the grounded shield of the line connecting to the center of the half-wave dipole where the potential node (zero-point) lies:



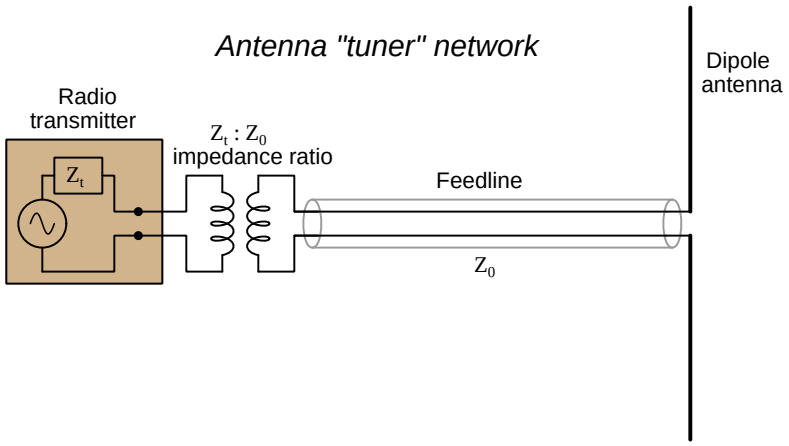
The gamma match assembly usually consists of two coaxially-arrange metal tubes with plastic insulation in between, the attachment point to the dipole being adjustable in position (dimension A) such that sliding that point of contact toward the antenna tip results in less capacitance (due to less overlapping tube area) between the coaxial tubes and more inductance formed by the enclosed area between the gamma match assembly and the dipole structure. Thus, the gamma match assembly forms a parasitic LC network accounting for its ability to transform the antenna's impedance.

Matching section, delta match, stub match, and gamma match networks all rely on precise physical dimensions to achieve the desired impedance match, and for this reason are only effective within a narrow range of signal frequencies. By contrast, a transformer-based impedance matching network may handle a much wider range of signal frequencies because the transformation is based on a turns ratio rather than networks of L and C with reactance values varying with frequency and/or networks of cables relying on standing waves having a particular fraction of the signal's wavelength. Thus, transformer matching networks are considered *wideband* and the others *narrowband*.

3.6 Transceiver impedance matching

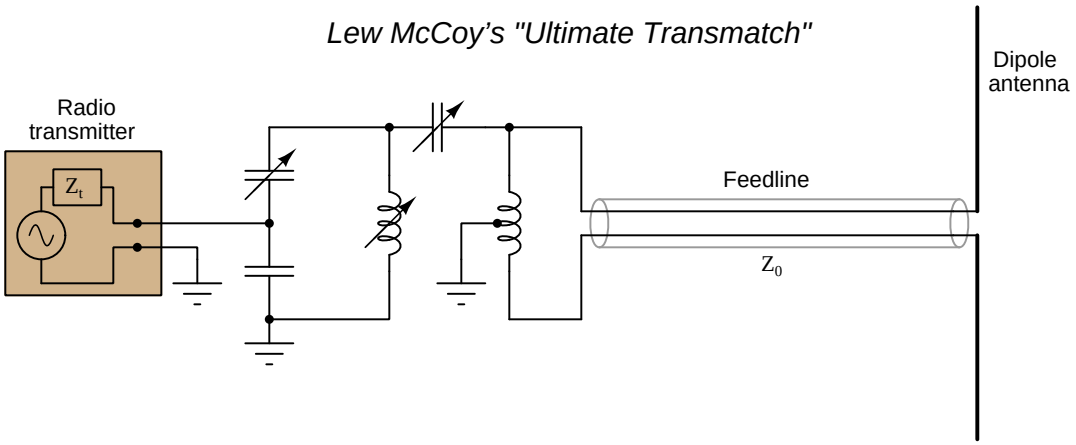
As previously reviewed, maximum power is transferred to a load from any source when that load's impedance equals the source's internal (Thévenin) impedance. For radio transmitters the concern is that the amount of impedance presented to the transmitter at that end of the feedline matches the output impedance of the transmitter's RF amplifier. If not, the energy reflected off of the interface between the amplifier and feedline may be sufficient to damage the amplifier's power-stage components. For radio receivers the concern is that not all of the precious energy collected by the antenna will be delivered to the receiver, but rather some of it will be reflected back into the feedline where it will either dissipate in the form of heat (cable losses) or be re-radiated back into space by the antenna.

When a significant impedance mismatch exists between the output of a transceiver and the feedline, we may use an interposing network to equalize the two. This network is (unfortunately) referred to as an *antenna tuner*, because it "tunes" (matches) the antenna/feedline *system* to have the same effective impedance as the transceiver. The basic principle is the same as with an antenna coupling network, and may take the form (or at least be modeled by) a transformer having the necessary turns ratio:



An important detail to note is that no impedance-matching network connected between the transmitter and the feedline is capable of correcting an impedance mismatch between the feedline and the antenna. If the feedline's characteristic impedance differs significantly from the antenna's feedpoint impedance, reflections of energy will still occur at that interface and standing waves will exist within the feedline. Those standing waves may still cause excessive energy loss within the feedline, and in some cases even insulation breakdown from excessive voltage at the anti-notes of those standing waves. However, energy transfer from the transmitter to the antenna system may still be improved with the matching network located at the transmitter's output.

Many antenna tuners, like antenna couplers, consist of discrete L and C components to perform the dual functions of impedance transformation and band-pass filtering (the latter to attenuate undesired harmonics). A classic example of an antenna tuner used in amateur radio is the "Ultimate Transmatch" invented by Lewis McCoy in 1970:

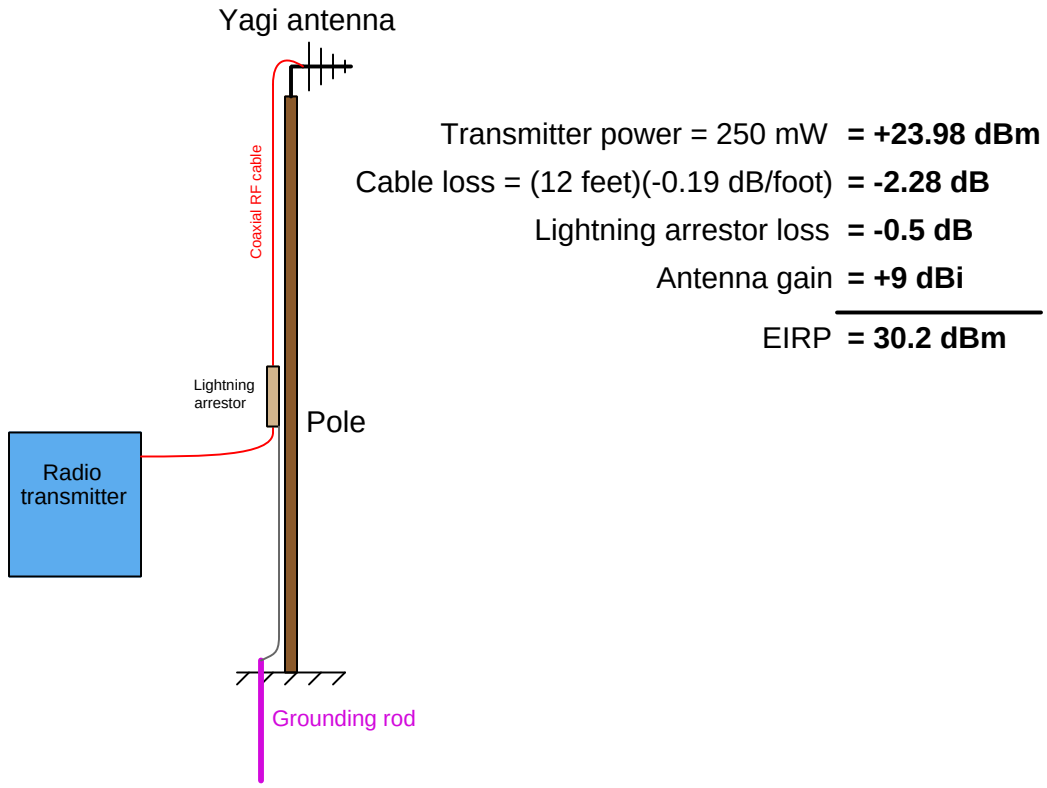


A matching network for a 50 kW AM broadcast transmitter is shown in the following photograph, with silver-coated inductor tubes to minimize resistance at high frequencies. The entire network is housed inside of a small shielded room, visible through the open door:

Impedance-matching networks are so useful that it is common to find them as a built-in feature in modern transceiver units.

3.7 Surge suppression and grounding

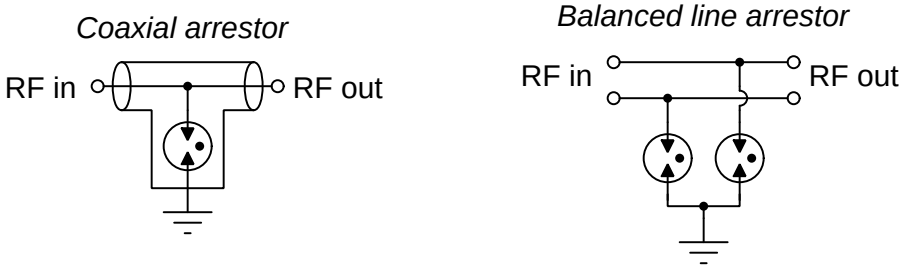
The elevated height of most antenna structures makes them uniquely susceptible to lightning strikes, and this necessitates over-voltage protection for the sake of the connected receiver(s) and/or transmitter(s). An example illustration is shown below, with a directional antenna connected to a radio transmitter via coaxial cable:



A *lightning arrestor* is a device providing a low-impedance pathway to Earth ground for any transient[8] current in an antenna system, for the purpose of "shunting" the lightning strike's energy harmlessly away from the connected radio equipment. Decibel ratings for each of the components in this antenna system are realistic for a low-power transmitter operating at 2.4 GHz, and as you can see the lightning arrestor unfortunately causes some power loss for the RF signals. This is inevitable, and must be factored into the radio system's RF power "budget".

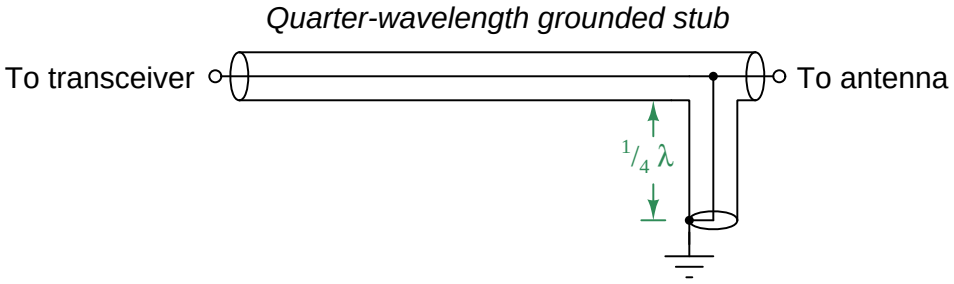
[8] A "transient" quantity is anything with a short duration. Here, we use the word "transient" to refer to potentially harmful surges of voltage and/or current.

One simple design of lightning arrestor uses one or more gas-discharge tubes as the current-shunting element(s). A photograph of such a device intended for use on a coaxial cable is shown below, followed immediately by typical schematic diagrams showing both coaxial and twin-conductor (balanced) line versions:



Gas-discharge tubes are essentially insulating unless and until a sufficient voltage is impressed between their electrodes, at which point the gas molecules between those electrodes ionize and become electrically conductive. Once the gas is conductive, it acts as a low-impedance "short" to allow the surge current to pass preferentially to the Earth rather than through the radio equipment. Although a relatively high voltage is necessary to initially ionize the gas, once ionized the gas "clamps" voltage to a much lower value and will not de-ionize until the surge energy dissipates.

A clever alternative to a gas-discharge tube is a *quarter-wave grounded stub* located close to the antenna structure. For coaxial cable systems this consists of a length of cable having the same characteristic impedance as the feedline, cut to a length of one-quarter wavelength with the center conductor shorted to the shield at the far end, and both connected to Earth ground. The other end of the quarter-wavelength stub of course connects to the feedline:



When operated at the correct frequency, the stub appears to be an "open" from the perspective of the feedline due to the standing voltage wave[9] set up along the stub's length, yet it provides a direct connection to Earth ground at all times for signals of different frequencies, including DC (zero frequency). In other words, a quarter-wave grounded stub effectively shorts all signals to ground except for the fundamental frequency of the radio system[10].

Another type of surge arrestor resembles a filter network, using an inductor to provide a low-impedance pathway to Earth ground for DC and low-frequency signals, and a capacitor to block DC from reaching the protected radio equipment:

[9] This standing wave will have its node (zero voltage) at the Earth-grounded end and its anti-node (full voltage) at the feedline.

[10] This statement is not *quite true*, as the stub will appear as an "open" not just to the fundamental frequency but also to its odd harmonics (i.e. any frequency creating a standing wave with a node at the Earth-ground end and an anti-node at the feedline for one-quarter of the fundamental's wavelength).

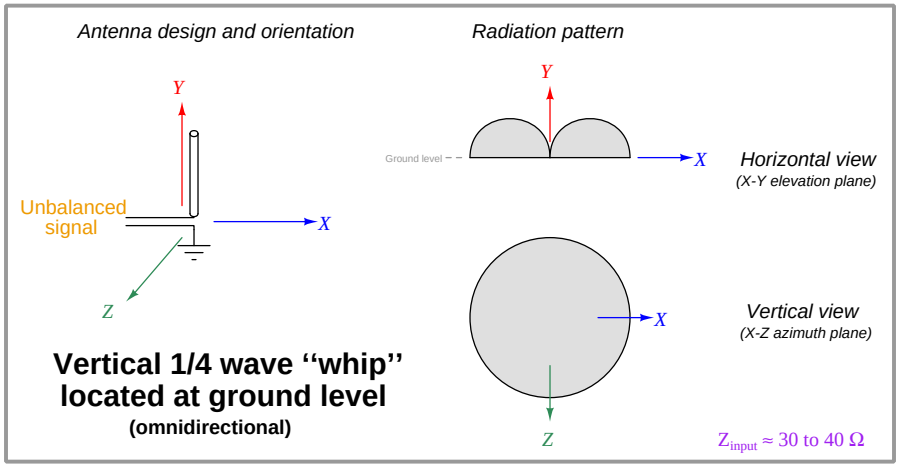
An easily-overlooked aspect of lightning protection is the Earth grounding to which any of these arrestor devices will connect. This ground connection should consist of at least one (preferably multiple) metal rods driven deep enough into the soil to provide a low-impedance Earth connection, with large cables connecting the ground rod(s) with the arrestor(s). Ground networks for commercial-scale radio antennas often consist of multiple grounding rods several feet in length forming an array radiating out from the antenna's base and surrounding any other structures (e.g. communications buildings), all connected together by conductors having a large surface area (for low resistance even at high frequencies, due to the *skin effect*[11]).

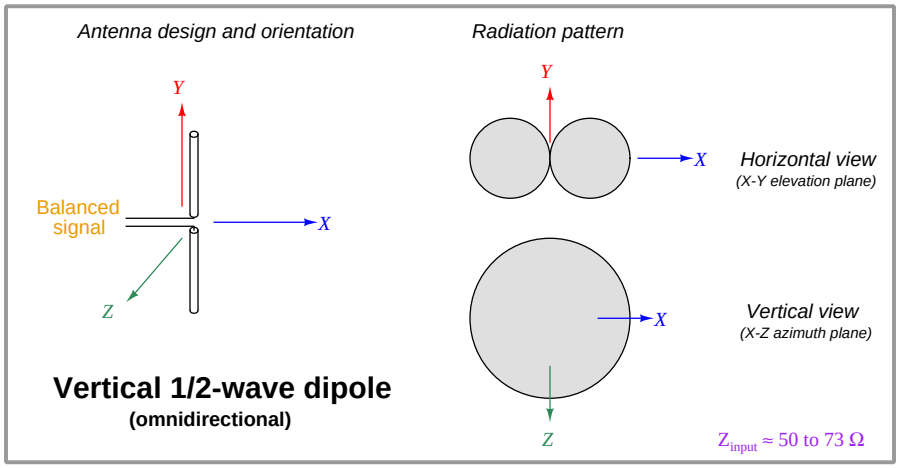
The following photograph shows a pair of wide copper ground straps connecting the Earth to a shelter's internal grounding network. Inside this shelter is an array of radio transceivers, all of which require a solid Earth ground connection, and this wide copper strapping provides that low-impedance connection by virtue of its large surface area:

[11] At very high frequencies electric currents tend to avoid traveling near the center of a solid conductor and instead concentrate near its "skin" (surface), making the surface area of any RF conductor more important for ampacity and resistance than its cross-sectional area.

3.8 Baluns and ununs

Antenna designs may be roughly divided into two types: those relying on a "ground plane" such as the Earth as one of the antenna elements, and those whose elements are isolated from ground. The classic quarter-wave "whip" antenna is an example of the former type, while the half-wave "dipole" is an example of the latter:

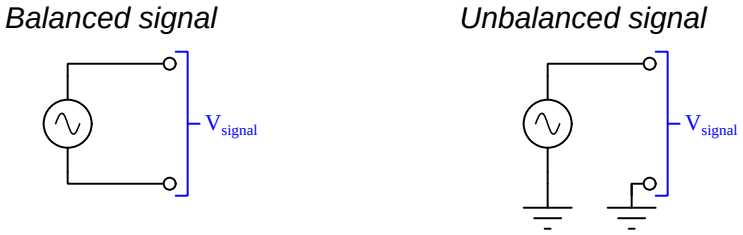




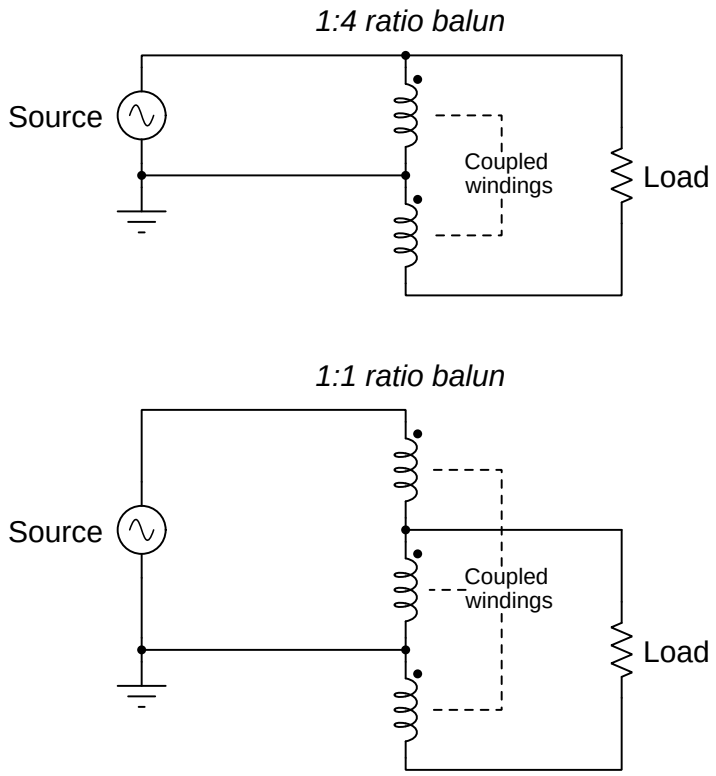
Note how the feedline for the "whip" or *monopole* antenna has one of its conductors bonded to Earth (ground) at the antenna location, whereas the dipole antenna's feedline has two ungrounded conductors. A "solid" ground connection is critical to the proper operation of a monopole antenna, because this type of antenna relies on a conductive surface beneath it for proper radiation and reception. On boats the surface of the water serves as this ground plane, and proper connection must be made to it from the feedline (the hull of a metal boat makes an excellent connection point). Some monopole antennas, especially those elevated significantly far from ground level, use an array

of horizontal or angled wires beneath it called a *counterpoise* as the ground plane. Interestingly, the configuration of this counterpoise array has a significant effect on the antenna's input impedance, and may be used to "tune" the antenna impedance to a more desirable value.

Any RF source, feedline, or antenna operating with both conductors at substantial voltage with respect to the Earth is called a *balanced* system, while a system operating with one of its two conductors at or near ground potential is called *unbalanced*:



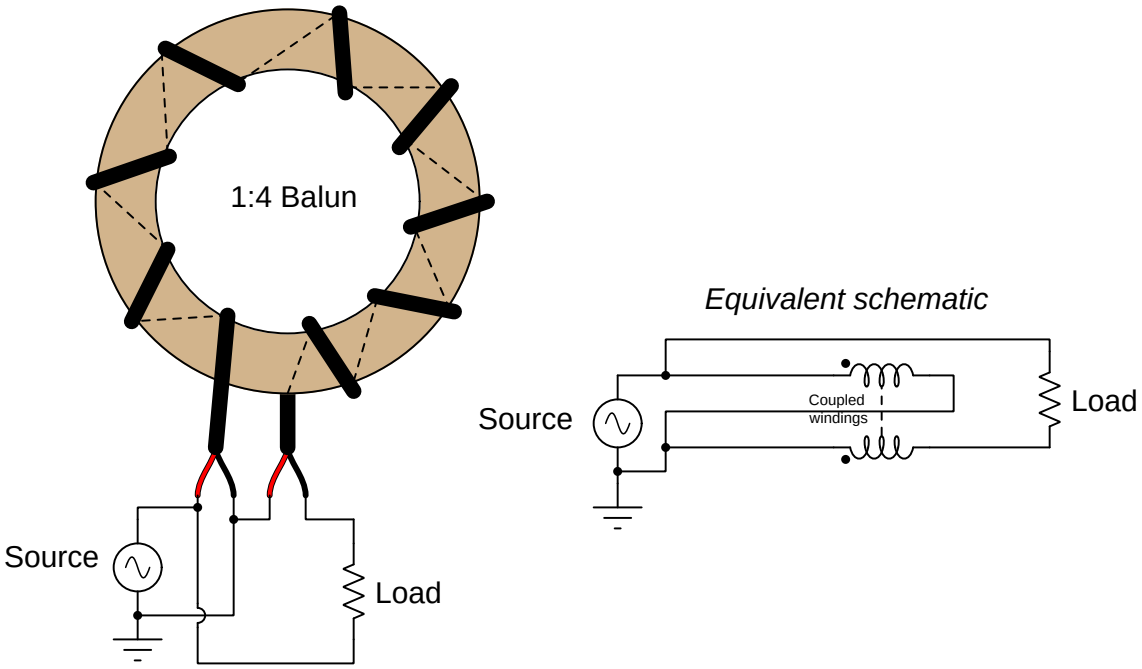
If radio equipment designed for one of these signal types must connect to an antenna of the other type, a special type of transformer called a *balun* (short for *balanced-unbalanced*) may be used between them. Two balun designs are shown below, in both cases an unbalanced source driving a balanced load (although the same circuits may certainly be used in reverse):



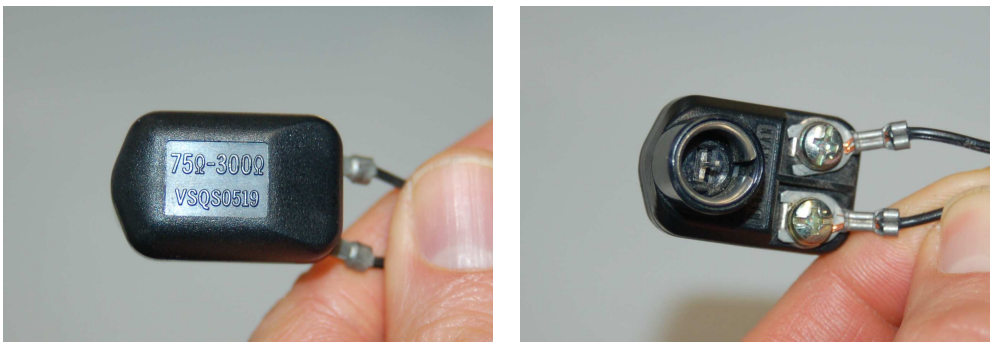
Assuming each of the wire windings possesses the same number of turns, the two-winding balun yields an impedance ratio of 1:4 (i.e. the source energizes N turns while the load is energized by $2N$ turns, yielding a 1:4 impedance ratio) while the three-winding balun exhibits a 1:1 impedance ratio (i.e. the source energizes $2N$ turns while the load is energized by $2N$ turns). In systems where a 1:4 ratio impedance match is necessary from an unbalanced system to a balanced system[12], the simpler balun performs both functions admirably.

[12]Such was the case for legacy analog television antenna systems which used a multi-element dipole antenna connected to 300 Ohm twin-lead cable, terminating at the 75 Ohm unbalanced input of the television receiver. The simple balun circuit transformed the 300 Ohm impedance of the antenna and cable into 75 Ohms for the sake of minimizing SWR, and also converted the antenna's balanced signal to the television receiver's unbalanced input circuitry.

Baluns are often made by wrapping a multi-conductor cable around a toroidal core[13]. The following illustration shows a two-winding (1:4 impedance ratio) balun using a single-pair cable with black and red conductors wrapped around a toroidal ferrite core, as well as its equivalent schematic diagram:

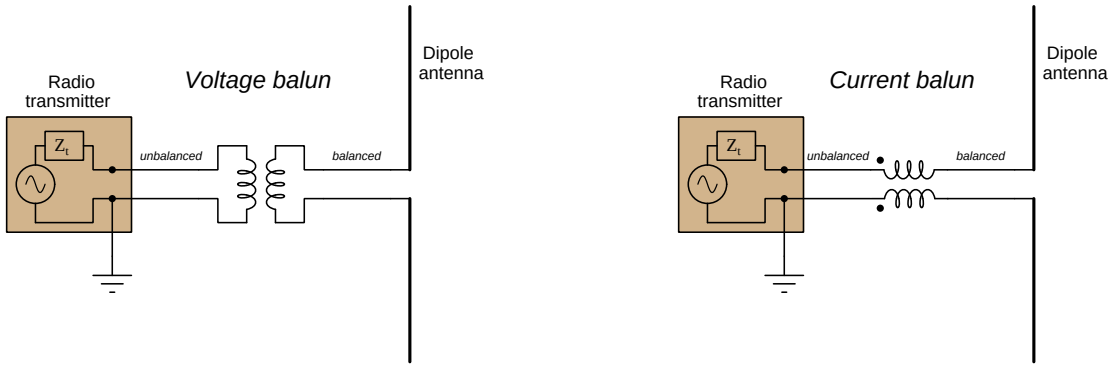


An example of a small 4:1 balun is shown here, converting the 300 Ohm impedance of a balanced television antenna (using twin-lead feedline) to the 75 Ohm impedance of the television receiver circuitry (using a coaxial connector):



[13]The core material is usually *soft ferrite*, this material type being chosen for its minimal eddy-current losses that would otherwise result in excessive power dissipation at radio frequencies.

Any balun so designed and connected as to place one or more of its windings in parallel with the transmitter's output, resulting in the winding(s) experiencing the transmitter's voltage and thus the balun's magnetic flux being a function of that applied voltage, is called a *voltage balun*. Any balun so designed and connected as to place one or more of its winding in series with the transmitter's output, resulting in the winding(s) experiencing the antenna current and thus the balun's magnetic flux being a function of that current, is called a *current balun*. Simple examples of each are shown below, both interfacing an unbalanced transmitter with a balanced antenna:



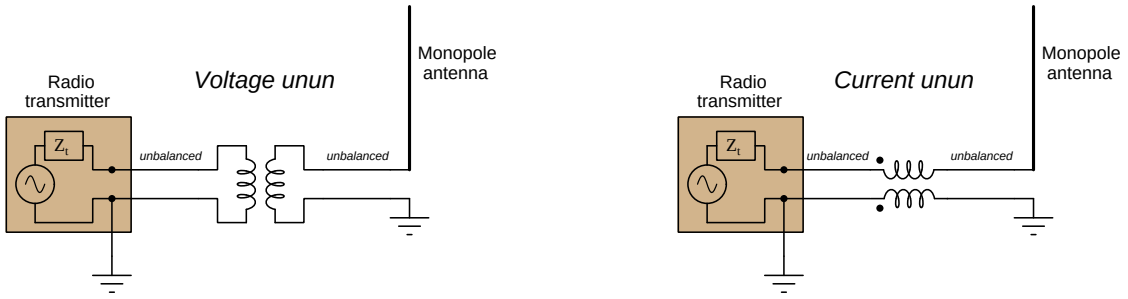
The voltage balun shown on the left is nothing but a simple voltage transformer, the left (primary) winding having one grounded terminal and the right (secondary) winding having no ground connection at all. The current balun is also known as a *common-mode choke*[14] and requires the two windings have matching polarities as shown. Differential (balanced) current between the transmitter and the antenna takes the form of equal currents flowing in opposite directions through the two windings, causing their magnetic fields to cancel and thus results in no magnetic flux. However, common-mode current between the transmitter and the antenna means currents flowing in the same direction through each winding, their magnetic fields adding. This results in a high inductive reactance placed in series with any common-mode current but zero inductive reactance to impede differential current, forcing the balanced antenna to have approximately equal (and opposite-direction) through its two elements which means it must function with potential between each element and Earth ground. The voltage balun as shown is capable of matching different impedances in addition to converting an unbalanced signal to a balanced, but the current balun is only capable of unbalanced/balanced conversion with no impedance matching.

Feedlines have been omitted from the above schematic diagrams for simplicity's sake, but it should be noted that the balanced/unbalanced nature of a feedline also needs to match the connection to any balun. That is to say, *everything* on the balanced side of a balun needs to be balanced (e.g. dipole antennas, twin-lead feedline) while *everything* on the unbalanced side of a balun needs to be unbalanced (e.g. unbalanced-output transmitter, coaxial cable). An example of an *incorrect* balun installation would be its unbalanced side connected directly to the output of an unbalanced transmitter, with coaxial cable feedline connecting to the balun's balanced side and running toward a dipole antenna; the error in this case being coaxial feedline experiencing balanced signals when it's designed to handle balanced (shield connected to Earth ground). In such a case the shield of

[14] For this reason, current baluns are sometimes referred to as *choking baluns*.

the coaxial cable will function as an extension of one side of the dipole antenna (radiating), while the center conductor will be completely shielded and non-radiating along the cable's length.

In applications where transmitter, feedline, and antenna are all unbalanced, we might use an unbalanced-to-unbalanced transformer, commonly referred to as an *unun*.



The voltage unun as shown is capable of matching unequal impedances by impedance ratio, but the current unun is merely capable of attenuating common-mode current between the transmitter and antenna. Current ununs are useful, though, for reducing common-mode *noise*, which is especially helpful in high-sensitivity *receiver* systems.

If building your own balun or unun using a toroidal powdered-iron core, the proper gauge of wire to use for the windings will be a function of maximum RF current, keeping in mind the *skin effect* which effectively reduces the ampacity of any wire due to the majority of RF current passing only through the "skin" of the conductor rather than through the entire cross-section of the conductor as is the case with DC and low-frequency AC. The number of turns of wire as well as the toroidal core's dimensions are more complicated to engineer. For voltage baluns the determining factors are the maximum RF voltage as well as the frequency, the goal being to avoid magnetically saturating the iron core material and to reduce hysteretic power losses in general, more turns allowing for the same amount of induced voltage for less-intense magnetic flux density in the core. For current baluns, a greater number of turns will result in more magnetic flux for any given amount of current.

Chapter 4

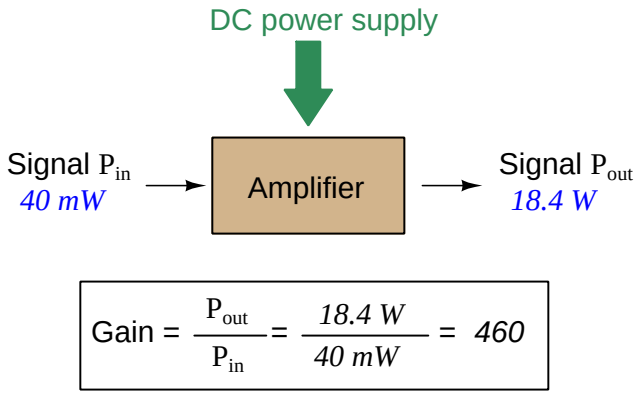
Derivations and Technical References

This chapter is where you will find mathematical derivations too detailed to include in the tutorial, and/or tables and other technical reference material.

4.1 Decibels

One of the mathematical tools popularly used to gauge increases and decreases of electrical power is the *common logarithm*, expressed as a measurement unit called the *decibel*. The basic idea of decibels is to express a ratio of two electrical power quantities in logarithmic terms. Every time you see the unit of "decibel" you can think: *this is an expression of how much greater (or how much smaller) one power is to another*. The only question is which two powers are being compared.

Electronic amplifiers are a type of electrical system where comparisons of power are useful. Students of electronics learn to compare the output power of an amplifier against the input power as a unitless ratio, called a *gain*. Take for example an electronic amplifier with a signal input of 40 milliWatts and a signal output of 18.4 Watts:



An alternative way to express the gain of this amplifier is to do so using the unit of the *Bel*, defined as the common logarithm of the gain ratio:

$$\log\left(\frac{P_{out}}{P_{in}}\right) = \log\left(\frac{18.4\text{ W}}{40\text{ mW}}\right) = 2.66276\text{ B}$$

When you see an amplifier gain expressed in the unit of "Bel", it's really just a way of saying "The output signal coming from this amplifier is x powers of ten greater than the input signal." An amplifier exhibiting a gain of 1 Bel outputs 10 times as much power as the input signal. An amplifier with a gain of 2 Bels boosts the input signal by a factor of 100. The amplifier shown above, with a gain of 2.66276 Bels, boosts the input signal 460-fold.

At some point in technological history it was decided that the "Bel" (B) was too large and cumbersome, and so it became common to express powers in fractions of a Bel instead: the *deci*Bel (1 dB = $\frac{1}{10}$ of a Bel). Therefore, this is the form of formula you will commonly see for expressing electrical signal power gains or losses:

$$\text{dB} = 10\log\left(\frac{P_{out}}{P_{in}}\right)$$

The gain of our hypothetical electronic amplifier, therefore, would be more commonly expressed as 26.6276 dB rather than 2.66276 B, although either expression is technically valid[1].

[1] It is interesting to note that although the "Bel" is a metric unit, it is seldom if ever used without the metric prefix

An operation students often struggle with is converting a decibel figure back into a ratio, since the concept of logarithms seems to be universally perplexing. Here I will demonstrate how to algebraically manipulate the decibel formula to solve for the power ratio given a dB figure.

First, we will begin with the decibel formula as given, solving for a value in decibels given a power ratio:

$$\text{dB} = 10 \log(\text{Ratio})$$

If we wish to solve for the ratio, we must "undo" all the mathematical operations surrounding that variable. One way to determine how to do this is to reverse the order of operations we would follow if we knew the ratio and were solving for the dB value. After calculating the ratio, we would then take the logarithm of that value, and then multiply that logarithm by 10: start with the ratio, then take the logarithm, then multiply last. To un-do these operations and solve for the ratio, we must un-do each of these operations in reverse order. First, we must un-do the multiplication (by dividing by 10):

$$\frac{\text{dB}}{10} = \frac{10 \log(\text{Ratio})}{10}$$

$$\frac{\text{dB}}{10} = \log(\text{Ratio})$$

Next, we must un-do the logarithm function by applying its mathematical inverse to both sides of the formula – making each expression a power of 10:

$$10^{\frac{\text{dB}}{10}} = 10^{\log(\text{Ratio})}$$

$$10^{\frac{\text{dB}}{10}} = \text{Ratio}$$

To test our algebra, we can take the previous decibel value for our hypothetical amplifier and see if this new formula yields the original gain ratio:

$$\text{Ratio} = 10^{\frac{26.6276 \text{ dB}}{10}}$$

$$\text{Ratio} = 10^{2.66276 \text{ B}}$$

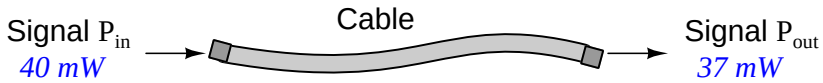
$$\text{Ratio} = 460$$

Sure enough, we arrive at the correct gain ratio of 460, starting with the decibel gain figure of 26.6276 dB.

"deci" ($\frac{1}{10}$). One could express powers in microbels, megabels, or any other metric prefix desired, but it is never done in industry: only the decibel is used.

We may also use decibels to express power *losses* in addition to power *gains*. There are many practical applications of this in signaling systems, both electronic and optical. One such application is *filtering*, where a "filter" circuit screens out certain components of the signal while letting others pass through (e.g. the bass or treble control for an audio system). Another application is *attenuation*, where the entirety of a signal is reduced in magnitude (e.g. the volume control for an audio system).

We will explore yet another application of signal power reduction as a case study for decibels: *cable loss*. Cables designed to convey signals over long distances are not perfect conduits of energy, as some of the signal's energy is inevitably lost along the way. This is true for different types of signals, electrical and optical being two popular examples. In the following illustration we see a signal cable losing power along its length[2], such that the power out is less than the power in:



$$\text{Gain} = \frac{P_{out}}{P_{in}} = \frac{37\ mW}{40\ mW} = 0.925$$

$$10 \log \left(\frac{P_{out}}{P_{in}} \right) = 10 \log \left(\frac{37 \text{ mW}}{40 \text{ mW}} \right) = -0.3386 \text{ dB}$$

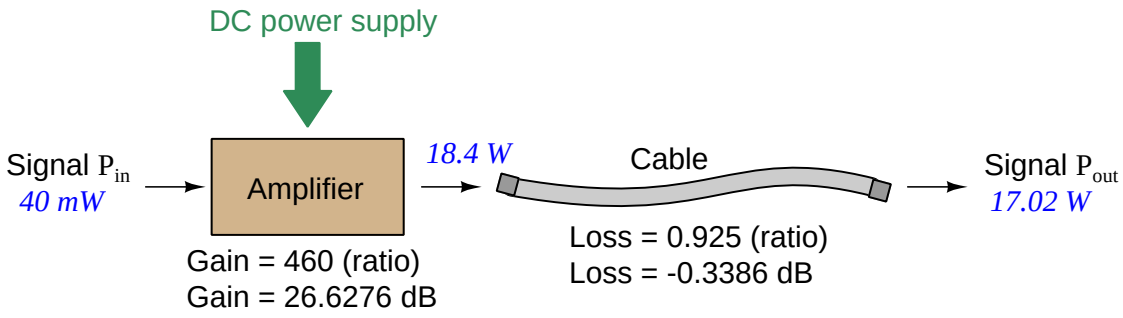
Contrasting this result against the previous result (with the amplifier) we see a very important property of decibel figures: any power *gain* is expressed as a *positive* decibel value, while any power *loss* is expressed as a *negative* decibel value. Any component outputting the exact same power as it takes in will exhibit a "gain" value of 0 dB (equivalent to a gain *ratio* of 1).

Remember that Bels and decibels are nothing more than logarithmic expressions of "greater than" and "less than". Positive values represent powers that are *greater* while negative values represent powers that are *lesser*. Zero Bel or decibel values represent *no change* (neither gain nor loss) in power.

A couple of simple decibel values are useful to remember for approximations, where you need to quickly estimate decibel values from power ratios (or vice-versa). Each addition or subtraction of 10 dB exactly represents a 10-fold multiplication or division of power ratio: e.g. +20 dB represents a power ratio gain of $10 \times 10 = 100$, whereas −30 dB represents a power ratio reduction of $\frac{1}{10} \times \frac{1}{10} \times \frac{1}{10} = \frac{1}{1000}$. Each addition or subtraction of 3 dB approximately represents a 2-fold multiplication or division or power ratio: e.g. +6 dB is approximately equal to a power ratio gain of $2 \times 2 = 4$, whereas −12 dB is approximately equal to a power ratio reduction of $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{16}$. We may combine ± 10 dB and ± 3 dB increments to come up with ratios that are products of 10 and 2: e.g. +26 dB is approximately equal to a power ratio gain of $10 \times 10 \times 2 \times 2 = 400$.

[2]For high-frequency signals such as those used in radio communications, the dominant mode of energy dissipation is *dielectric heating*, where the AC electric field between the cable conductors excites the molecules of the conductor insulation. This energy loss manifests as heat, which explains why there is less signal energy present at the load end of the cable than is input at the source end of the cable. For DC and low-frequency AC circuits the dominant mode of energy dissipation is cable conductor resistance, which is typically very small.

Observe what happens if we combine a "gain" component with a "loss" component and calculate the overall power out versus power in:



The overall gain of this amplifier and cable system expressed as a ratio is equal to the *product* of the individual component gain/loss ratios. That is, the gain ratio of the amplifier *multiplied* by the loss ratio of the cable yields the overall power ratio for the system:

$$\text{Overall gain} = \frac{17.02 \text{ W}}{40 \text{ mW}} = (460)(0.925) = 425.5$$

The overall gain may be alternatively expressed as a decibel figure, in which case it is equal to the *sum* of the individual component decibel values. That is, the decibel gain of the amplifier *added* to the decibel loss of the cable yields the overall decibel figure for the system:

$$\text{Overall gain} = 10 \log \left(\frac{17.02 \text{ W}}{40 \text{ mW}} \right) = 26.6276 \text{ dB} + (-0.3386 \text{ dB}) = 26.2890 \text{ dB}$$

It is often useful to be able to estimate decibel values from power ratios and vice-versa. If we take the gain ratio of this amplifier and cable system (425.5) and round it down to 400, we may easily express this gain ratio as an expanded product of 10 and 2:

$$425.5 \approx 400 = (10) \times (10) \times (2) \times (2)$$

Knowing that every 10-fold multiplication of power ratio is an addition of +10 dB, and that every 2-fold multiplication of power is an addition of +3 dB, we may express the expanded product as a sum of decibel values:

$$(10) \times (10) \times (2) \times (2) = (10 \text{ dB}) + (10 \text{ dB}) + (3 \text{ dB}) + (3 \text{ dB}) = 26 \text{ dB}$$

Therefore, our power ratio of 425.5 is approximately equal to +26 decibels.

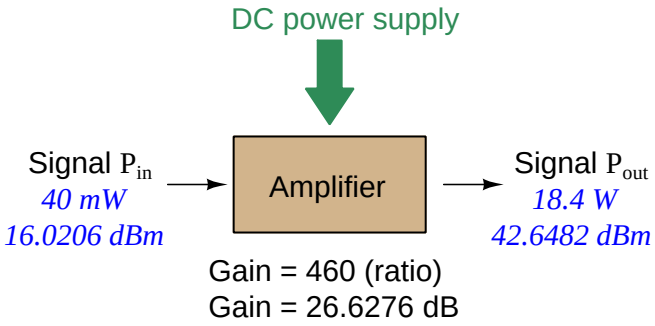
Decibels always represent comparisons of power, but that comparison need not always be P_{out}/P_{in} for a system component. We may also use decibels to express an amount of power compared to some standard reference. If, for example, we wished to express the input power to our hypothetical amplifier (40 milliWatts) using decibels, we could do so by comparing 40 mW against a standard "reference" power of exactly 1 milliWatt. The resulting decibel figure would be written as "dBm" in honor of the 1 *m*illiWatt reference:

$$P_{in} = 10 \log \left(\frac{40 \text{ mW}}{1 \text{ mW}} \right) = 16.0206 \text{ dBm}$$

The unit of "dBm" literally means the amount of dB "greater than" 1 milliWatt. In this case, our input signal of 40 milliWatts is 16.0206 dB greater than a standard reference power of exactly 1 milliWatt. The output power of that amplifier (18.4 Watts) may be expressed in dBm as well:

$$P_{out} = 10 \log \left(\frac{18.4 \text{ W}}{1 \text{ mW}} \right) = 42.6482 \text{ dBm}$$

A signal power of 18.4 Watts is 42.6482 dB greater than a standard reference power of exactly 1 milliWatt, and so it has a decibel value of 42.6482 dBm.



Notice how the output and input powers expressed in dBm relate to the power gain of the amplifier. Taking the input power and simply *adding* the amplifier's gain factor yields the amplifier's output power in dBm:

$$P_{in}(\text{dB}) + P_{gain}(\text{dB}) = P_{out}(\text{dB})$$

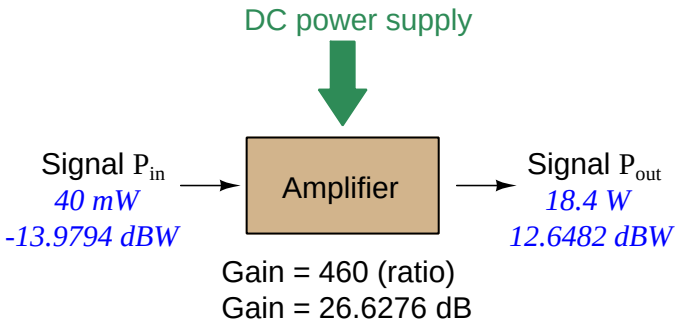
$$16.0206 \text{ dBm} + 26.6276 \text{ dB} = 42.6482 \text{ dBm}$$

An electronic signal that begins 16.0206 dB greater than 1 milliWatt, when boosted by an amplifier gain of 26.6276 dB, will become 42.6482 dB greater than the original reference power of 1 milliWatt.

We may alternatively express all powers in this hypothetical amplifier in reference to a 1-Watt standard power, with the resulting power expressed in units of "dBW" (decibels greater than 1 Watt):

$$P_{in} = 10 \log \left(\frac{40 \text{ mW}}{1 \text{ W}} \right) = -13.9794 \text{ dBW}$$

$$P_{out} = 10 \log \left(\frac{18.4 \text{ W}}{1 \text{ W}} \right) = 12.6482 \text{ dBW}$$



Note how the input power of 40 milliWatts equates to a negative dBW figure because 40 milliWatts is *less* than the 1 Watt reference, and how the output power of 18.4 Watts equates to a positive dBW figure because 18.4 Watts is *more* than the 1 Watt reference. A positive dB figure means "more than" while a negative dB figure means "less than."

Note also how the output and input powers expressed in dBW still relate to the power gain of the amplifier by simple addition, just as they did when previously expressed in units of dBm. Taking the input power in units of dBW and simply *adding* the amplifier's gain factor yields the amplifier's output power in dBW:

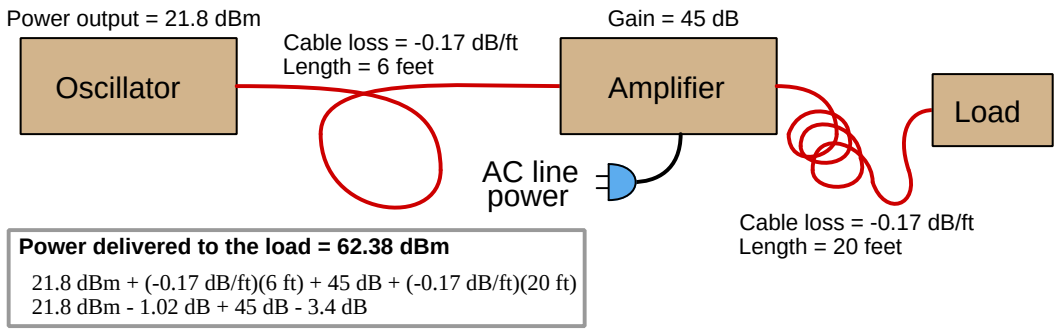
$$P_{in}(\text{dB}) + P_{gain}(\text{dB}) = P_{out}(\text{dB})$$

$$-13.9794 \text{ dBW} + 26.6276 \text{ dB} = 12.6482 \text{ dBW}$$

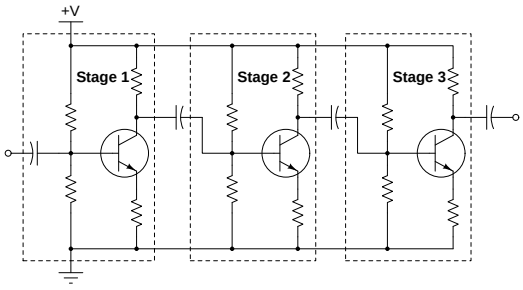
An electronic signal that begins 13.9794 dB less than 1 Watt, when boosted by an amplifier gain of 26.6276 dB, will become 12.6482 dB greater than the original reference power of 1 Watt.

This is one of the major benefits of using decibels to express powers: we may very easily calculate power gains and losses by summing a string of dB figures, each dB figure representing the power gain or power loss of a different system component. Normally, any compounding of *ratios* involves multiplication and/or division of those ratios, but with decibels we may simply add and subtract. One of the interesting mathematical properties of logarithms is that they "transform[3]" one type of problem into a simpler type: in this case, a problem of multiplying ratios into a (simpler) problem of adding decibel figures.

For example, we may express the power dissipated along a cable in terms of decibels per foot; the longer the cable, of course, the more power will be lost this way, all other factors being equal. For example, a radio-frequency signal cable having a loss figure of −0.15 decibels per foot at a signal frequency of 2.4 GHz will suffer −15 dB over 100 feet, and −150 dB over 1000 feet. To illustrate how decibels may be used to calculate power delivered to a load in such a system, accounting for various gains and losses along the way using decibel figures:



A similar application of decibels is found in multi-stage amplifier circuits, where one stage amplifies a signal to be fed into a successive stage to be amplified more. The power gains of these stages, each expressed as a ratio, *multiply* to make the over-all amplifier's power gain (ratio). The power gains of those same stages, each expressed as a decibel figure, *add* to make the over-all amplifier's power gain (dB):



[3]In fact, logarithms are one of the simplest examples of a *transform function*, converting one type of mathematical problem into another type. Other examples of mathematical transform functions used in engineering include the *Fourier transform* (converting a time-domain function into a frequency-domain function) and the *Laplace transform* (converting a differential equation into an algebraic equation).

Another common application of decibels is to express ratios of voltage and/or current rather than power. However, since the unit of the Bel has been defined as an expression of a *power* ratio, we cannot simply substitute V or I for P in any of the formulae we've seen so far.

Suppose an amplifier has a voltage gain of 2 (i.e. V_{out} is twice as large as V_{in}), and we would like to express this gain in decibels. Since decibels are intended to express power gain and not voltage gain, we must figure out how much power gain is equivalent to a voltage gain of two. Obviously, voltage and power are fundamentally different quantities, but if we imagine ourselves connecting a fixed load resistance to the input signal, and then to the output signal, we will realize that load's power dissipation will be more than double when energized by a voltage twice as large. Joule's Law is helpful to determine the exact ratio of power dissipation:

$$P = \frac{V^2}{R}$$

Doubling voltage for any given load resistance results in power *quadrupling* because power is proportional to the square of the voltage applied to a fixed resistance. Using this as the basis for applying decibels to a voltage ratio. Knowing that Joule's Law also declares power is proportional to the square of the current applied to a fixed resistance ($P = I^2R$) means this same mathematical relationship will apply to current gains and reductions as well as voltage gains and reductions:

$$\text{dB} = 10 \log \left(\frac{P_{out}}{P_{in}} \right) = 10 \log \left(\frac{V_{out}}{V_{in}} \right)^2 = 10 \log \left(\frac{I_{out}}{I_{in}} \right)^2$$

An algebraic identity of logarithms is that the logarithm of any quantity raised to a power is equal to that power multiplied by the logarithm of the quantity. Expressed in general terms:

$$\log x^y = y \log x$$

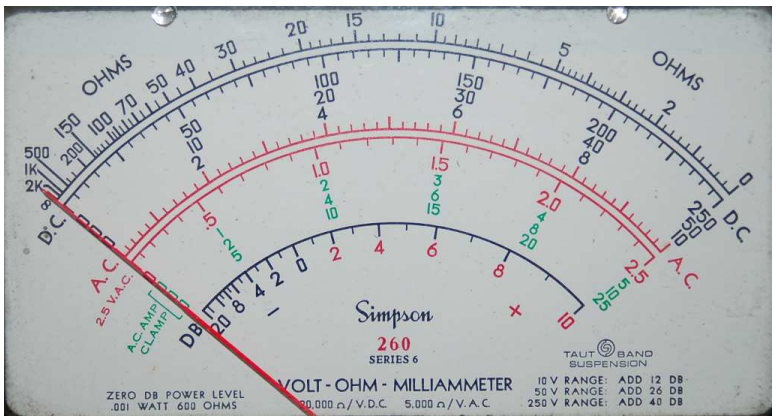
Therefore, we may simplify the decibel formula for voltage gain by removing the "2" power and making it a multiplier:

$$10 \log \left(\frac{V_{out}}{V_{in}} \right)^2 = (2)(10) \log \left(\frac{V_{out}}{V_{in}} \right) = 20 \log \left(\frac{V_{out}}{V_{in}} \right)$$

$$10 \log \left(\frac{I_{out}}{I_{in}} \right)^2 = (2)(10) \log \left(\frac{I_{out}}{I_{in}} \right) = 20 \log \left(\frac{I_{out}}{I_{in}} \right)$$

Thus, we may use decibels to express voltage or current ratios if we simply substitute 20 instead of 10 as the multiplier.

We can see the practicality of using decibels to represent something other than electrical *power* by examining this analog meter face, belonging to a Simpson model 260 VOM (Volt-Ohm-Milliammeter). Note the bottom scale on this meter's face, calibrated in decibels (DB):



Pay attention to the note on decibels written in the lower-left corner of the meter face, where 0 dB is defined as 0.001 Watt dissipated by 600 Ohms. The fact that 0 dB is defined as 1 milliWatt means it should (properly) be labeled dBm rather than dB[4]. A load resistance value is necessary as part of this definition for dB because this meter cannot measure power directly but must infer signal power from measurements of AC *voltage*. Without a specific load resistance, there is no clear relation between voltage and power. 600 Ohms is an old telecommunications standard for audio-frequency AC signals, and continues to be used today for voltage-based decibel measurements of audio-frequency AC signals.

The meter as shown is connected to nothing at all, and so registers 0 Volts AC. This, of course, corresponds to zero power, and it has no corresponding decibel value because the logarithm of zero is mathematically *undefined*[5]. Practically, it means $-\infty$ dB, which is why the needle at the 0 Volt position "falls off" the left-hand end of the dB scale.

Close inspection of the dB scale on this meter face reveals another interesting property of decibels, and that is the *nonlinear* nature of the dB scale. This contrasts starkly against all the voltage and current scales on this meter face which are linear. This nonlinearity is a fundamental property of decibels because it is based on the *logarithm* function which is nonlinear.

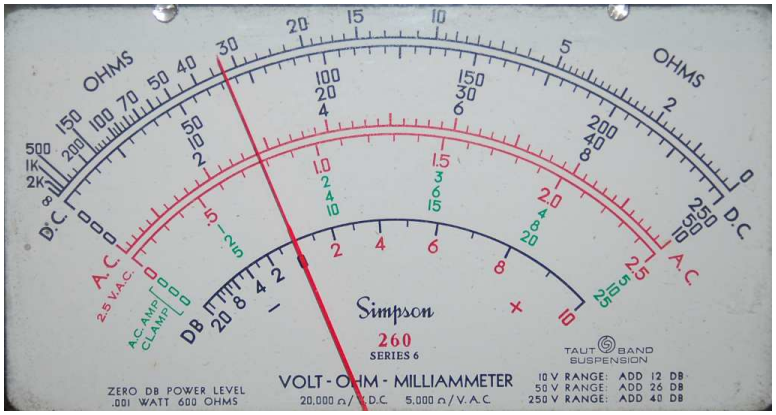
[4] Such mis-labeling is not that uncommon in the profession, the expectation being that the technician or engineer working with the instrument ought to be familiar enough with the concept of decibels to know when dB really means dBm, or dBW, etc.

[5] Your electronic calculator will complain if you attempt to take the logarithm of zero!

Now, we will explore what is necessary to make this meter register 0 dBm (i.e. 1 milliWatt) with an applied AC voltage. 1 milliWatt of power dissipated by 600 Ohms is equivalent to:

$$V = \sqrt{PR} = \sqrt{(0.001)(600)} = 0.7746 \text{ Volts}$$

Setting the VOM to the 2.5 VAC range and applying just enough AC voltage to bring the needle to the 0 dB mark allows us to verify that this is indeed equivalent to just under 0.8 Volts (read on the 2.5 VAC scale):



In the lower-right corner of the meter face we see some notes regarding correction values for decibel measurements when using different AC voltage ranges. The dB scale is read directly when the meter is set on the 2.5 VAC range. When set on the 10 VAC range (i.e. a range *four times* as great), the meter's needle will experience a deflection one-fourth as much as when set to the 2.5 VAC range, and therefore it will point to a lesser (or even negative) value on the dB scale. Converting a voltage ratio of 0.25 into a decibel figure shows us how much less the needle will register on the dB scale when the voltage range is quadrupled:

$$20 \log \left(\frac{2.5}{10} \right) = -12.04 \text{ dB}$$

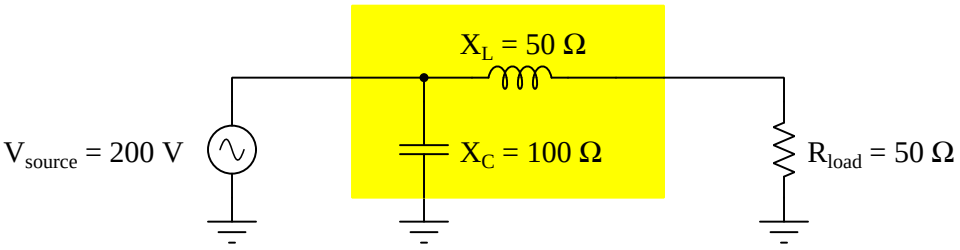
Therefore, when using the 10 VAC range instead of the 2.5 VAC range, one must add 12 dB to the reading. Likewise, we may prove each of the printed correction factors for the alternative voltage-measurement ranges listed (50 Volt AC range and 250 Volt AC range):

$$20 \log \left(\frac{2.5}{50} \right) = -26.02 \text{ dB}$$

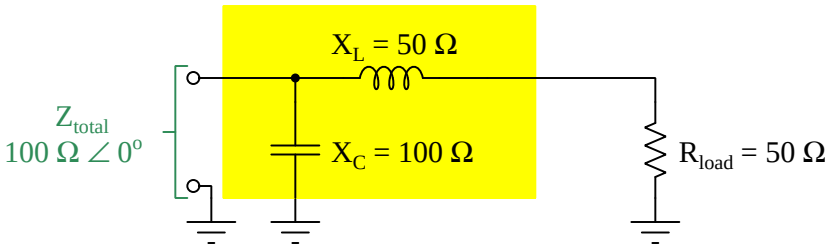
$$20 \log \left(\frac{2.5}{250} \right) = -40.0 \text{ dB}$$

4.2 LC impedance-transformation networks

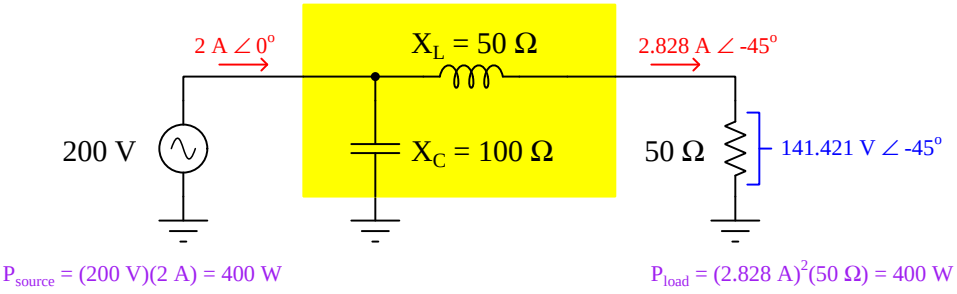
An interesting and useful property of inductor-capacitor networks is their ability to make the impedance of a load "look" different to a connected source. As an example of this, consider the following network connected between a 200 Volt AC source and a 50 Ohm resistive load. In order to keep this example as simple as possible, we specify reactance values for the inductor and capacitor rather than actual inductance and capacitance values (along with a specified source frequency):



If we perform the necessary series-parallel impedance calculations for the LC network and resistive load, we find that the total impedance (as calculated from the perspective of the input terminal where the source would connect) is precisely 100 Ohms resistive (i.e. $100\ \Omega \angle\ 0^o$ or $100 + j0$) which is twice the impedance of the load with the same phase angle.

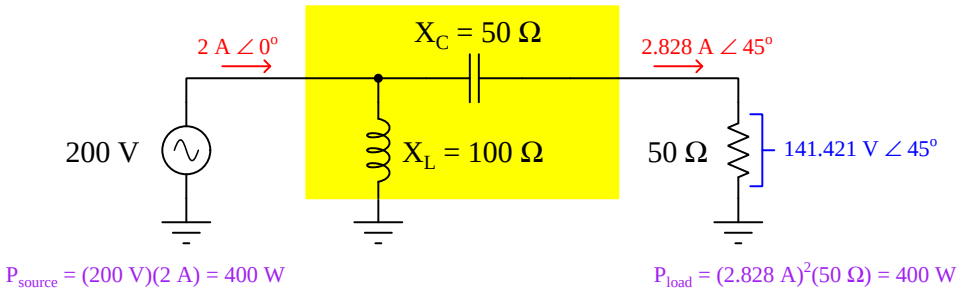


Therefore, when this circuit is energized we find the following voltage, currents, and powers at the source and load:



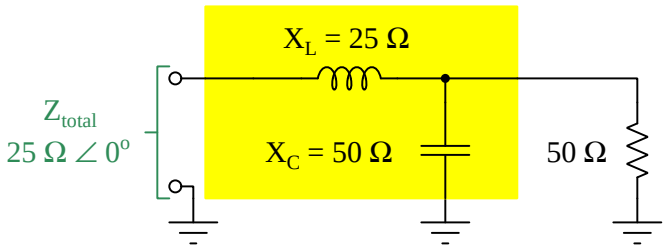
Note how with the simple LC network the source "sees" a 100 Ohm load impedance even though the actual load is 50 Ohms, and also how load power and source power are precisely equal (at least given an ideal inductor and an ideal capacitor having no dissipative losses).

We may achieve the same load impedance transformation by exchanging the placement of the inductor and capacitor, but maintaining the original reactance values (50 Ohms in series, 100 Ohms in parallel). The only difference is in the phase shift of current and voltage at the 50 Ohm resistive load:

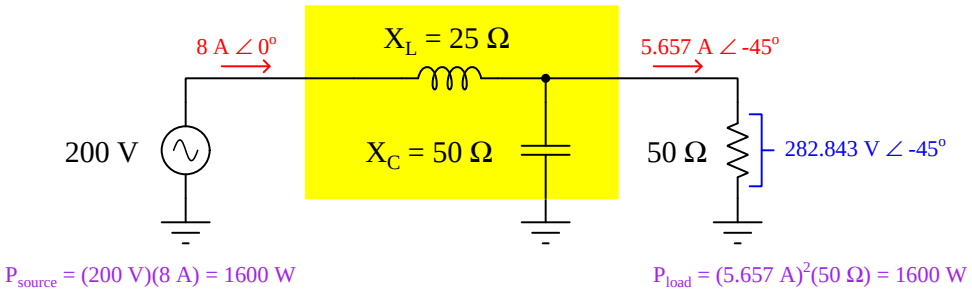


One way to view these LC impedance-transformation networks conceptually is to view the series-connected component (with the load) as adding to the load's impedance, and the parallel-connected component (with the source) correcting that increased impedance to become purely resistive as seen by the source.

It is also possible to transform a resistive load's impedance *down* rather than up, by altering the series-parallel relationship of the reactive components and suitably altering their reactance values. In this case, the LC network transforms the 50 Ohm resistive load into 25 Ohms as "seen" by the AC source:



Therefore, when this circuit is energized we find the following voltage, currents, and powers at the source and load:

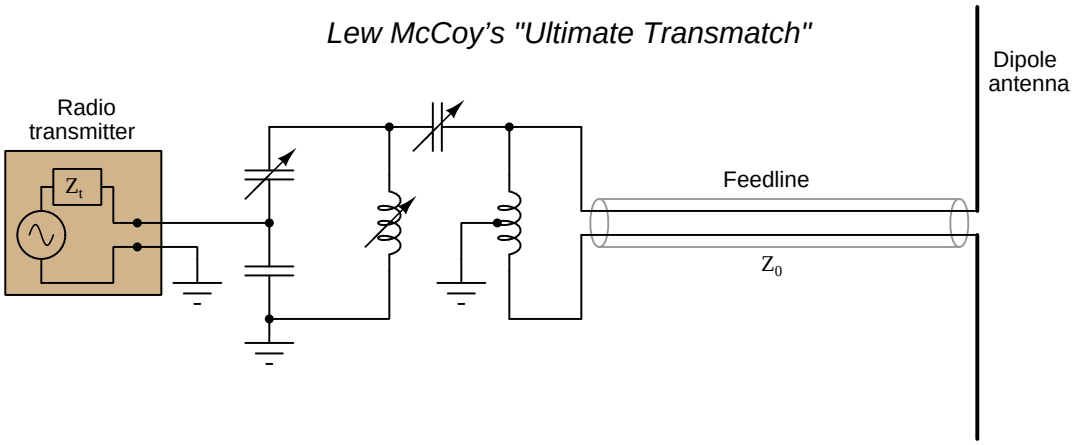


Again, we may conceptually understand these LC impedance-transformation networks by considering the parallel-connected component as a means to diminish the load's apparent impedance, and considering the series-connected component as a means to cancel out any remaining reactance so that the source sees a purely resistive load. The reason this network decreases the load's apparent impedance is because the component connected directly to the load is in *parallel*, while the former network increased the load's apparent impedance because the component connected directly to the load was in *series*.

As before with the impedance-boosting network, we may swap the positions of L and C and achieve the same effect if the reactance values remain the same (i.e. 50 Ohm inductive reactance in parallel with the 50 Ohm load resistance and 25 Ohm capacitive reactance in series with the source).

Impedance transformation occurs because capacitors and inductors are (ideally) non-dissipative components. Stacking inductance and capacitance in a series-parallel network with a load obviously alters the total impedance value, thus making the load "appear" to have a different impedance than it does from the perspective of the source, but the non-dissipative nature of the LC network means no energy is "wasted" therein and the resistive load must receive all of the source's power. Just as a transformer with a turns ratio other than 1:1 clearly presents a different voltage to the load than what the source supplies, and given the non-dissipative nature of the transformer and the Law of Energy Conservation this *must* mean current gets transformed in the inverse ratio.

A common application of this impedance-transformation method is matching the impedance of an antenna and feedline system to the output impedance of a radio-frequency power amplifier, such as that found in a radio transmitter system. The principle involved here is the Maximum Power Transfer Theorem, which states the amount of power delivered to a load from a source is maximized when the load's impedance is adjusted to equal that of the source[6]. Proper impedance-matching between load and source is also necessary to minimize signal reflections and *standing waves* along transmission lines such as the feedlines connecting radio transceivers to their respective antennas. Often referred to as *transmatch* networks, an example of impedance transformation by an LC network[7] is found in Lew McCoy's "ultimate transmatch" designed for amateur radio operations:



Adjustable capacitors and inductors are typically provided in transmatch networks so that the radio operator may "align" the unit to the operating frequency of the transmitter as well as to the exact impedances of the amplifier and antenna/feedline system. McCoy's general instructions for using this particular network (as written in his July 1970 *QST* magazine article "The Ultimate Transmatch") include setting both variable capacitors to maximum capacitance, adjusting the variable inductor until minimum reflected power is obtained (i.e. as close to a perfect standing wave ratio as possible), and then adjusting variable capacitors C_1 and C_2 by trial-and-error until the best match is obtained, as indicated by the SWR reaching unity or reflected power decreasing

[6] This would be the source's equivalent Thévenin or Norton impedance.

[7] In fairness, McCoy's design also incorporates a wideband transformer at its output, accounting for a 1:4 impedance transformation of its own.

to zero. Although multiple combinations of C and L values are possible for matching any given transmitter to its line and antenna at a particular frequency, McCoy recommends optimizing for a solution using maximum capacitance[8].

A photograph of an impedance-matching network for a 50 kW AM broadcast transmitter operating at 550 kHz is shown in the following photograph, with silver-coated inductor tubes to minimize resistance at high frequencies[9]. The entire network is housed inside of a small shielded room, visible through the open door:

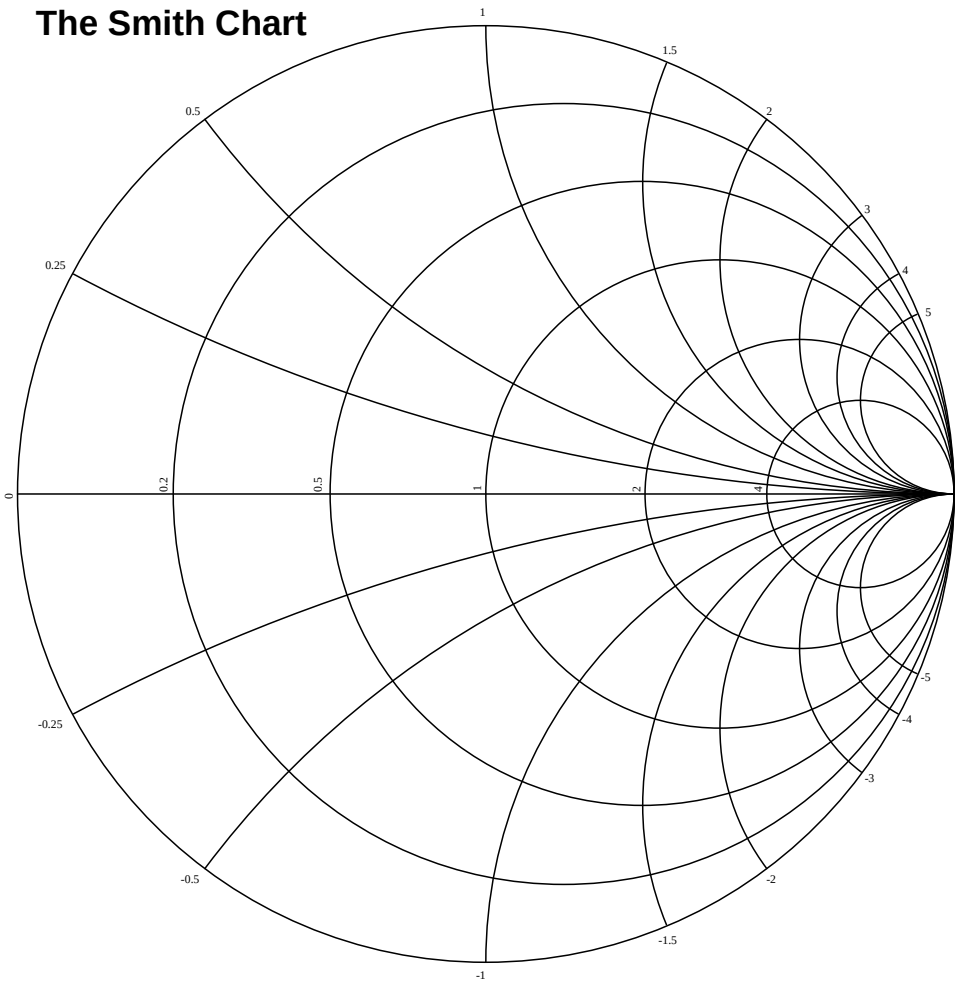
A caveat to this method of impedance transformation is that it only functions properly at (or near) one frequency value. Other impedance-transformation techniques such as *transformers* and *amplifiers* work over much broader frequency ranges.

[8] For example if a combination of high L and low C results in a good match, but another combination consisting of low L and high C also happens to result in a good match, the latter combination is preferable.

[9] At radio frequencies, the *skin effect* causes the majority of the current to travel on the outside surface of the conductor rather than the interior. Therefore, the electrical conductivity of the conductor's surface material matters more than its interior bulk. This is also why most RF conductors are hollow rather than solid metal: having a solid RF conductor would just be a waste of metal since nearly all of the current travels along the exterior surface.

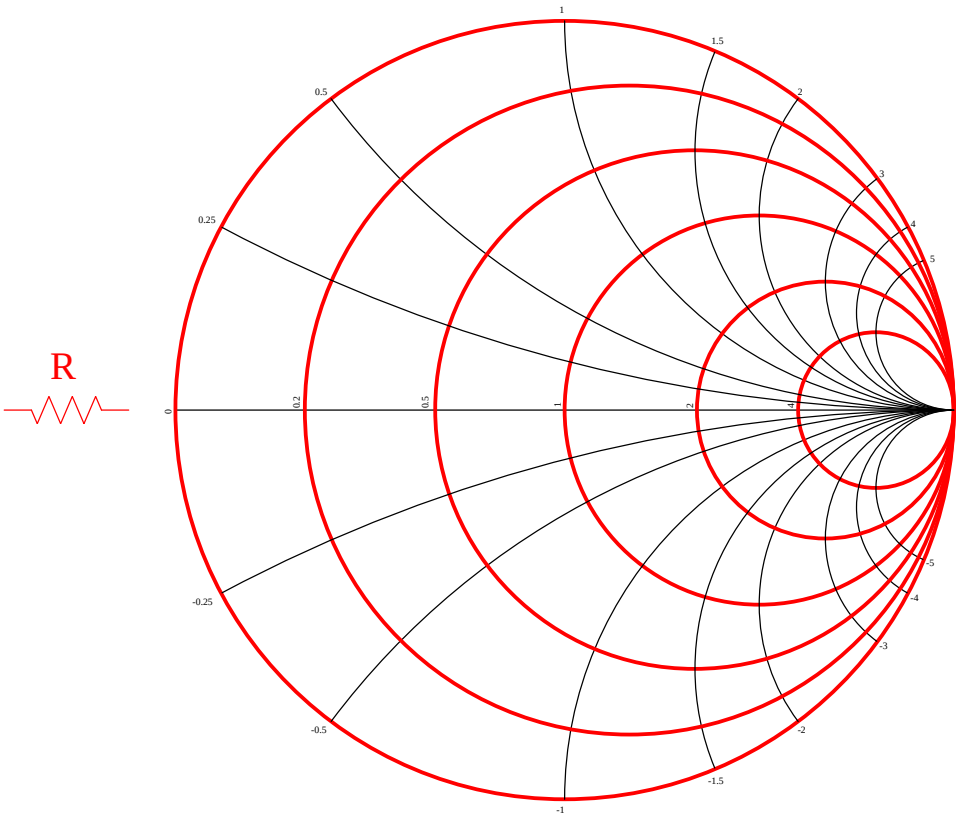
4.3 Smith charts

The *Smith chart* is a nomograph[10] useful for transmission line calculations where a mismatched load terminates the line. It is formed by two sets of intersecting circles, one set of circles centered along the horizontal axis representing normalized resistance values (i.e. termination resistance as a ratio of transmission line characteristic impedance) and another set of circles centered along the vertical axis representing normalized reactance values (i.e. termination reactance as a ratio of transmission line characteristic impedance):

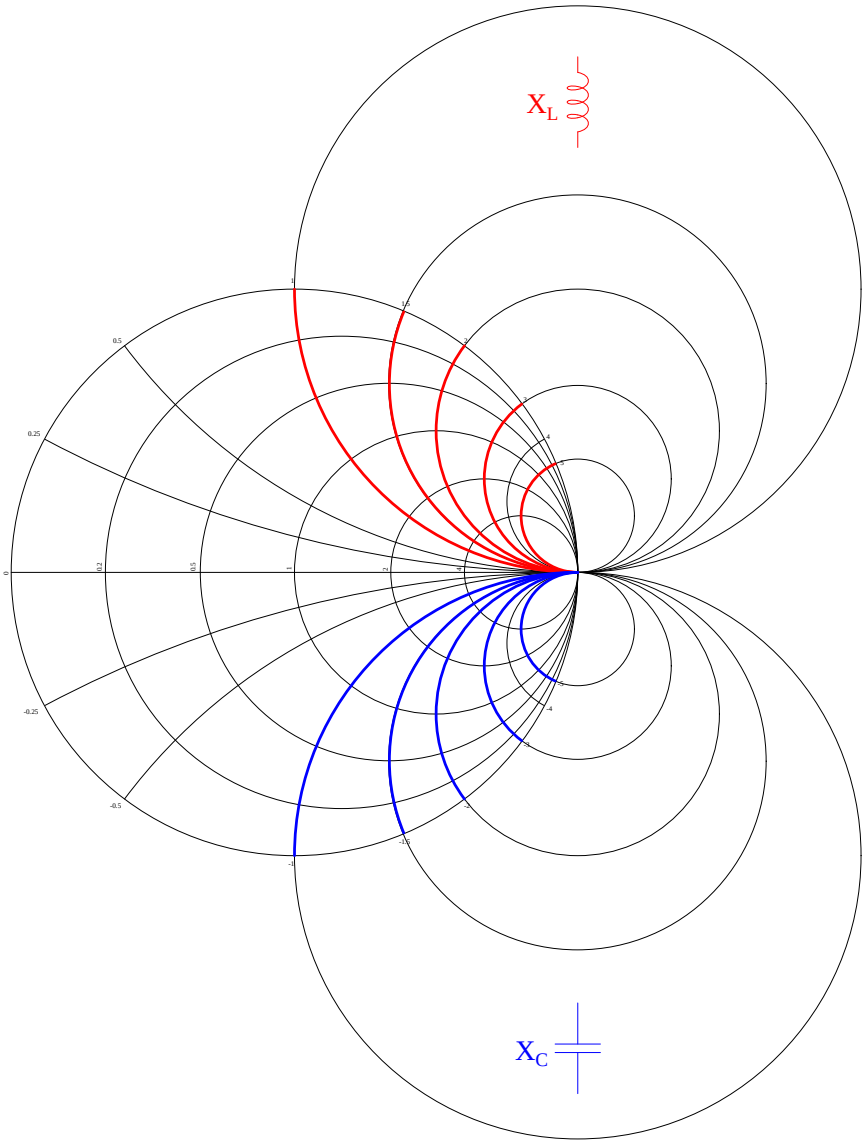


[10] A "nomograph" is any form of graphical calculating aid, where quantities are represented by positions along axes.

The resistance circles of a Smith chart lie along the horizontal axis and intersect at the far-right end of that axis, each one having a radius proportional to $\frac{1}{R+1}$ where R is the *normalized* resistance of the terminating impedance (i.e. the terminating impedance's resistance value divided by the transmission line's characteristic impedance value of 50 Ω):

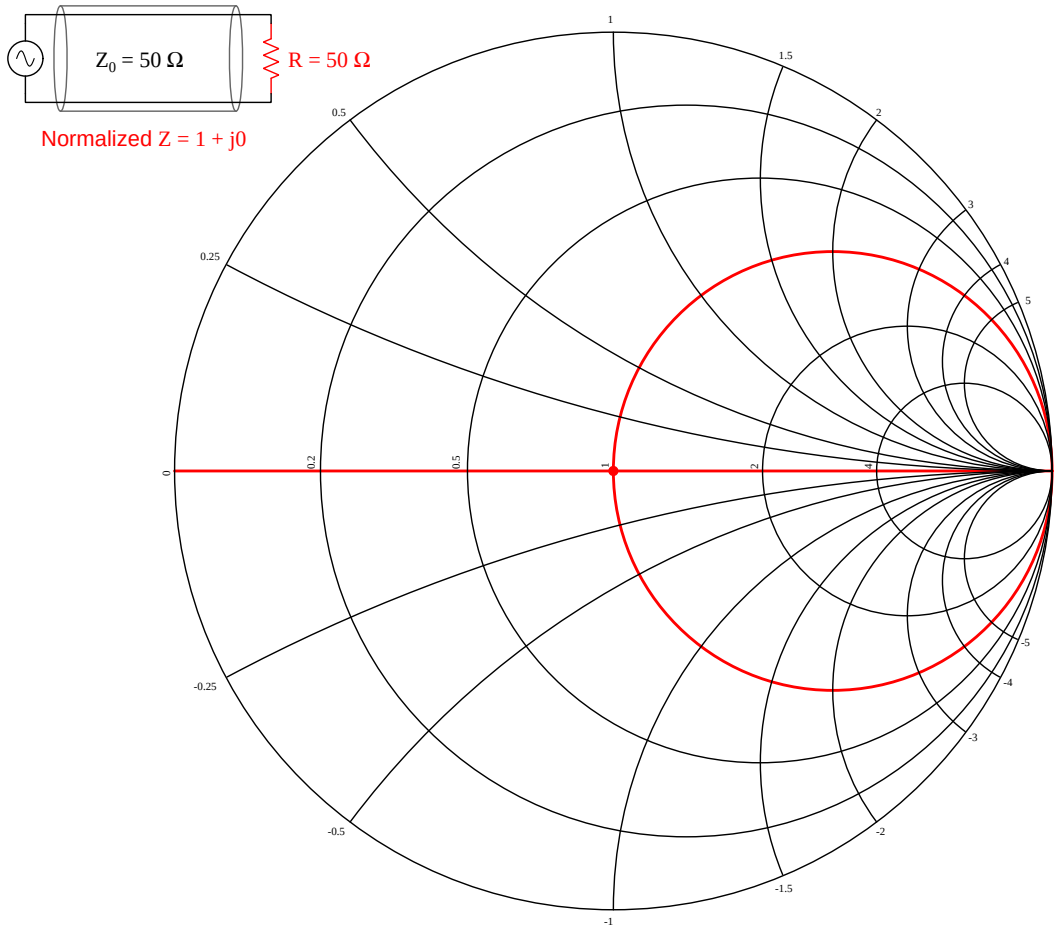


The reactance circles of a Smith chart lie along the vertical axis and intersect at the far-right end of the horizontal axis, each one having a radius proportional to $\frac{1}{X}$ where X is the *normalized* reactance of the terminating impedance (i.e. the terminating impedance's reactance value divided by the transmission line's characteristic impedance value of 50 Ω):



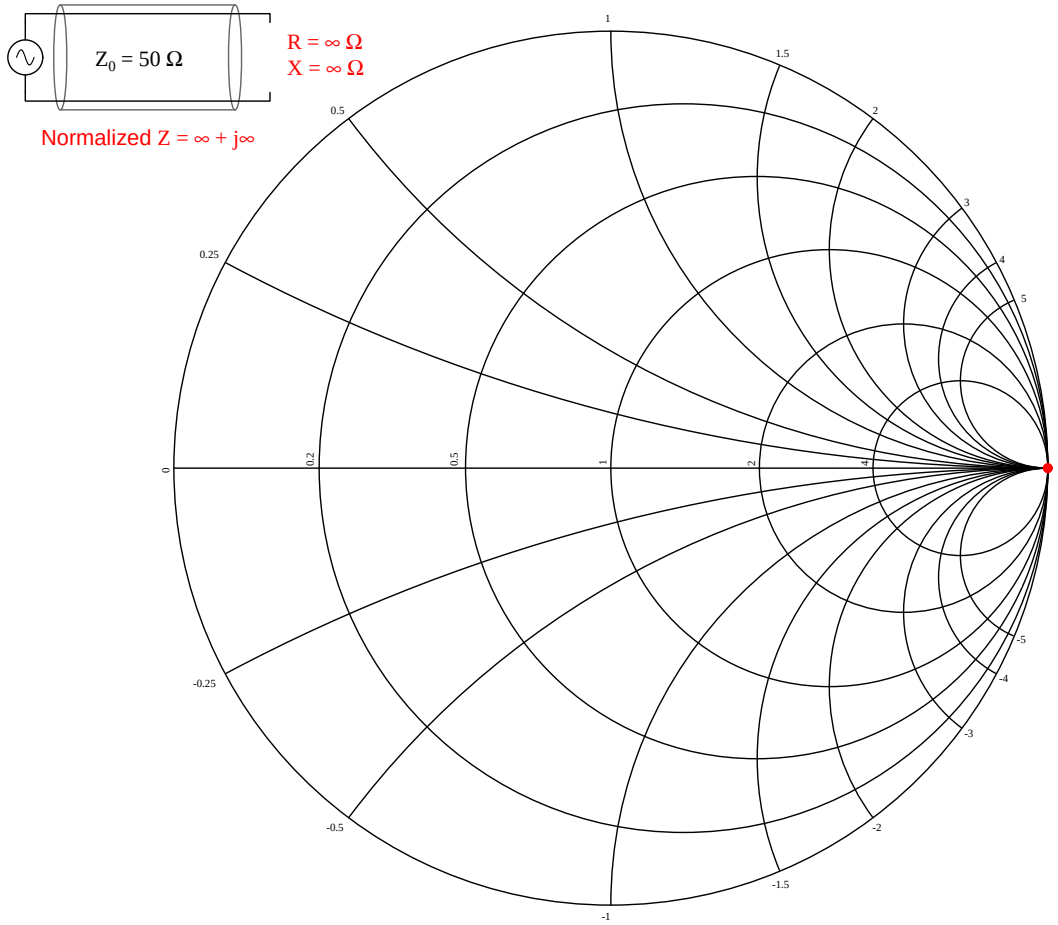
Inductive reactance values are positive (above the horizontal axis) while capacitive reactance values are negative (below the horizontal axis).

If the transmission line is perfectly terminated, in this case the 50 Ω line being terminated by a 50 Ω resistance, the normalized value of this terminating impedance will be $1 + j0$ which places it at the exact center of the Smith chart:



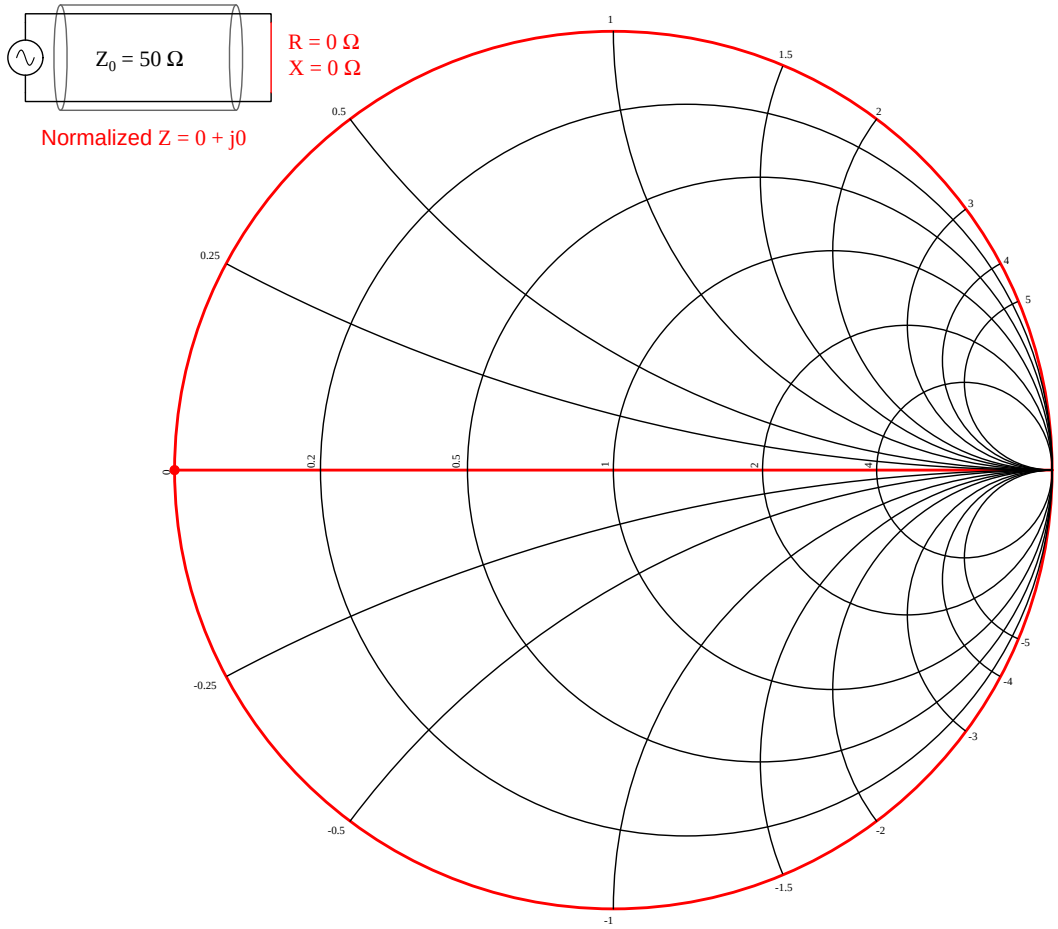
This is the point marked by the intersection of the "1" resistance circle and the "0" reactance circle (i.e. a "circle" with an infinite radius which is really a straight line overlapping the horizontal axis).

The limiting cases of an open-terminated transmission line is represented by a point with infinite resistance and reactance, located at the far-right end of the horizontal axis:



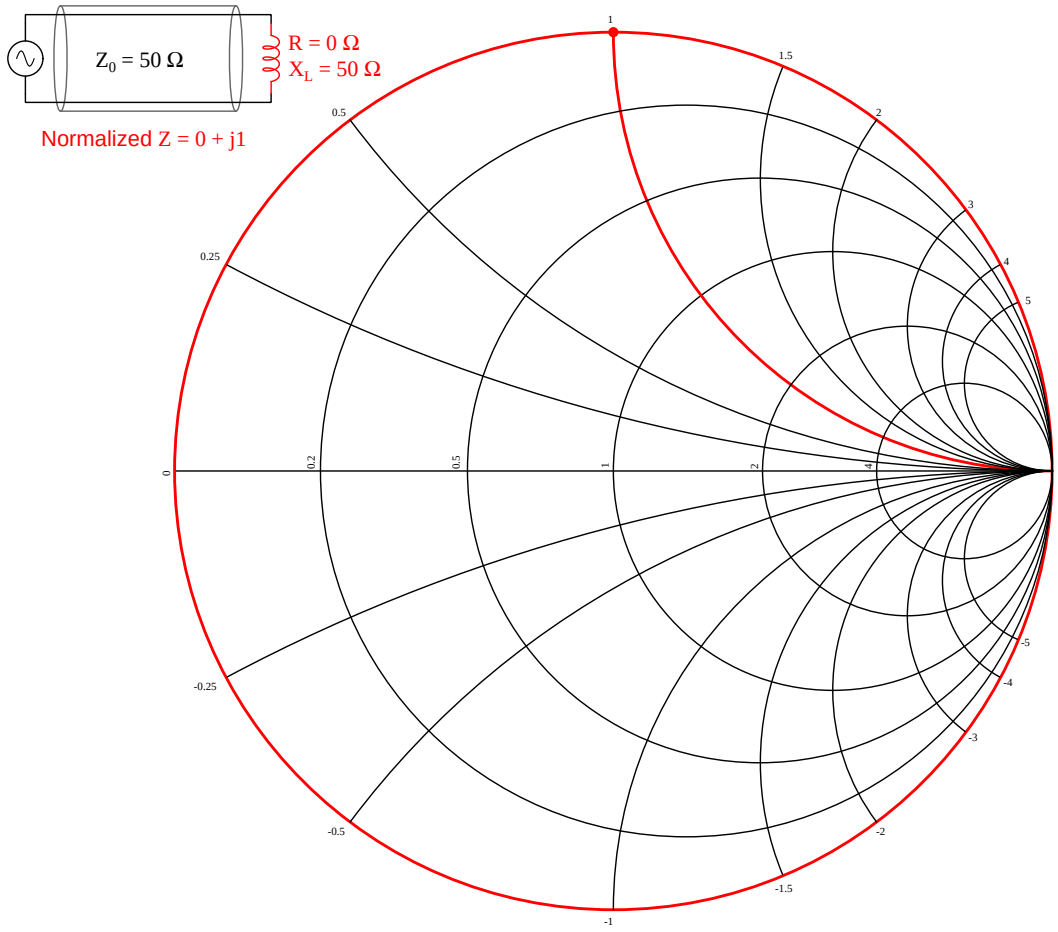
This is the point marked by the intersection of a zero-radius resistance circle and a zero-radius reactance circle.

The limiting cases of a short-terminated transmission line is represented by a point with zero resistance and reactance, located at the far-left of the horizontal axis:

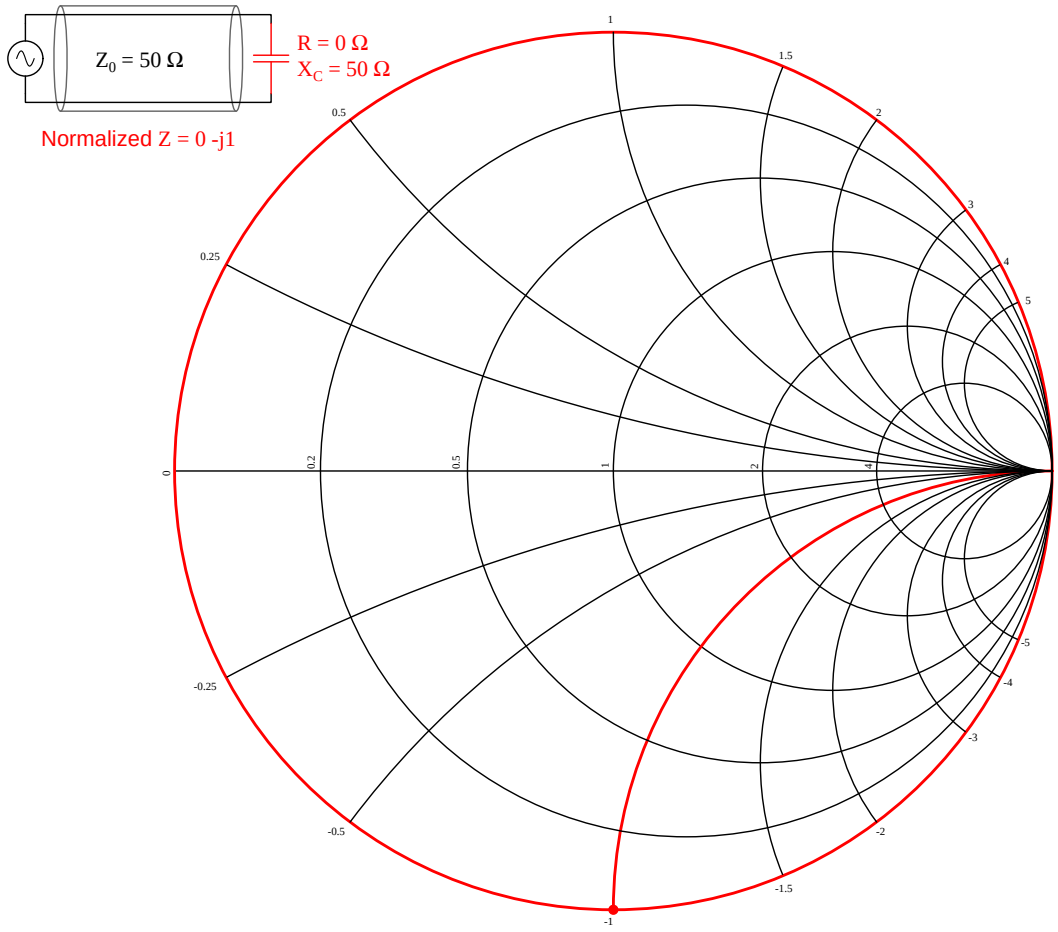


This is the point marked by the intersection of a full-radius resistance circle and a reactance circle having an infinite radius (i.e. a "circle" which is really a straight line overlapping the horizontal axis).

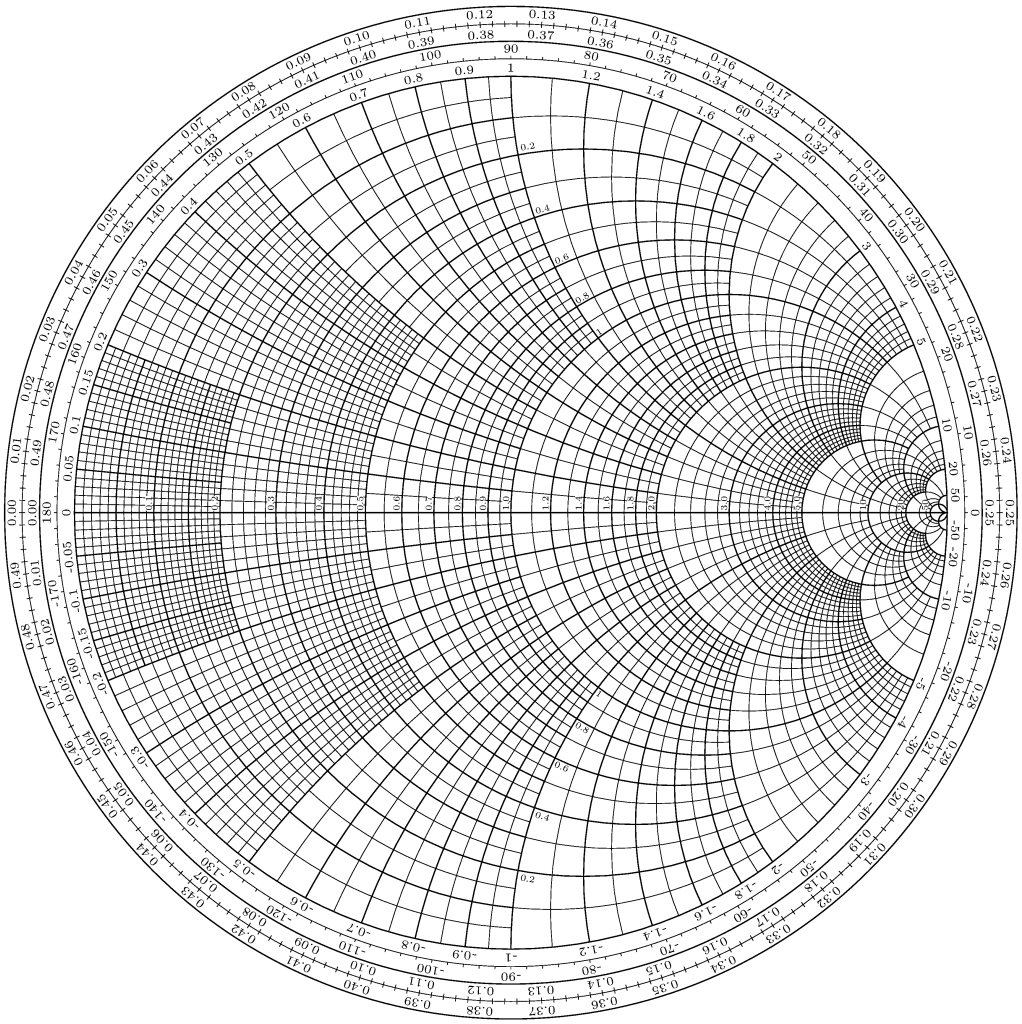
The upper half of the Smith chart is where all the inductive curves reside, which means if we terminate the 50 Ω transmission line with a pure inductance of 50 Ω the location will be where the +1 reactance circle intersects with the 0 resistance circle:



The lower half of the Smith chart is where all the capacitive curves reside, which means if we terminate the 50 Ω transmission line with a pure capacitance of 50 Ω the location will be where the −1 reactance circle intersects with the 0 resistance circle:



A practical Smith chart (courtesy of Germinal Camp[11]) is shown here:



[11] Germinal wrote code for a LaTeX document to draw this detailed Smith Chart, and from this source code one can generate a Postscript or PDF image. I took the Postscript output and converted that into an SVG image, which then imported well into Xcircuit where it is easier to overlay annotations.

4.4 The Poynting vector

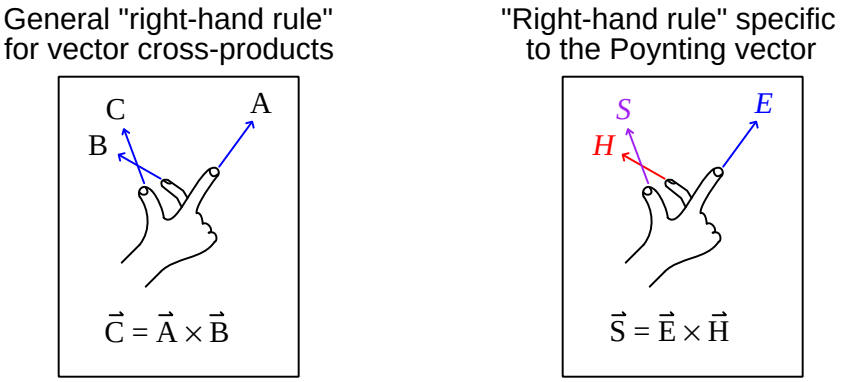
We know that electric fields (E) are always associated with a voltage (V), and magnetic fields (field strength B and field force H) with a current (I). Specifically, electric field strength is the quotient of voltage and distance between two points which is why electric fields are measured in units of *Volts per meter*. Similarly, magnetic field force around a straight current-carrying conductor is the quotient of current and circumference of the circular magnetic path (equal to 2π times the distance from the conductor) which is why magnetic field force is measured in units of *Amperes per meter*.

From Joule's Law we know that the rate of energy transfer (called power) whenever there is simultaneous voltage and current ($P = VI$). It stands to reason, then, that just as voltage multiplied by current yields power, an electric field multiplied by a magnetic field must similarly express power transferred by those two fields through space. That is, if $P = VI$, then the product of E and H should yield a power *intensity* which we shall label S:

$$P = VI \qquad \text{[Watts]} = \text{[Volts][Amperes]}$$

$$S = EH \qquad \text{[Watts/meter}^2\text{]} = \text{[Volts/meter][Amperes/meter]}$$

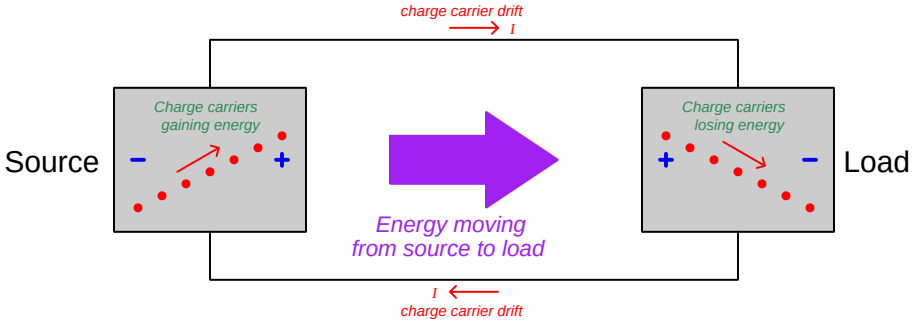
Notice how the Joule's Law equation $P = VI$ involves scalar quantities, while the $S = EH$ equation necessarily involves spatial dimensions of distance (meters) and area (square meters). This is because both electric and magnetic fields are *vector* quantities having both magnitude and spatial direction. Power intensity (S) is the measure of how much power is flowing per square meter of area in open space. As it so happens, power intensity in Watts per square meter relates to electric and magnetic fields by the right-hand rule of vector cross-products, the vector expression of that power intensity being called the *Poynting vector* ($\vec{S}$) after its formulator, the English physicist John H. Poynting:



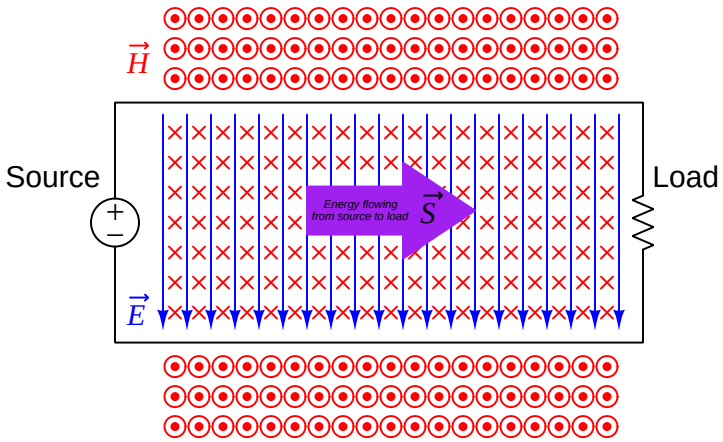
Poynting's contribution to the science of electromagnetism was expressing energy conservation and energy transfer in terms of electric and magnetic fields. That is, the electric and magnetic fields associated with any electrical *source* result in a flow of energy away from that source *through space*, and the electric and magnetic fields associated with any *load* result in a flow of energy toward that load *through space*. The direction of the Poynting vector shows the direction of that energy flow,

and the Poynting vector magnitude shows how many Watts of power flow per square meter of space.

This should be a rather startling conclusion to anyone familiar with voltage, current, and power in simple DC circuits. Beginning students of electricity regard energy transfer in simple circuits as the gain and loss of potential energy in mobile electric charges, those charges gaining energy as they pass through a source and losing energy as they pass through a load:

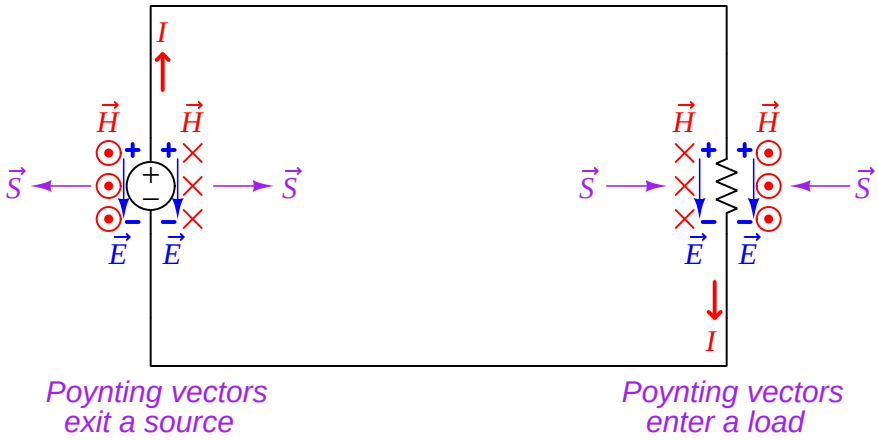


Though this model is conceptually correct, *so is Poynting's model of energy flowing through space*. In fact, if we re-draw this simple circuit illustration showing the electric and magnetic field vectors between the two wires, we can see the Poynting vector expressing that flow of energy from source to load[12]:



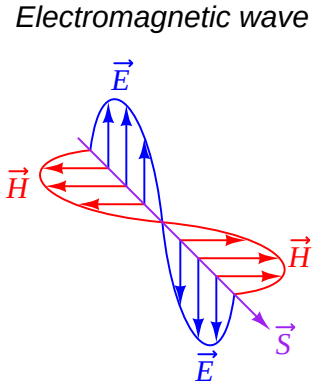
[12] Holding your right hand such that your index finger points downward ($\vec{E}$) and your middle finger into the page ($\vec{H}$), your thumb will point to the right ($\vec{S}$) from source to load.

If we examine the source and load separately using the right-hand rule, we see how the Poynting vector in each case shows the proper direction of energy transfer:



It is well-worth your time to apply the right-hand rule to each of the four Poynting vectors shown above, to familiarize yourself with the use of this tool as a means to determine vector cross-product directions. For example, to the left of the source we see the electric field vector pointing down which means your index finger should point downward as well. The magnetic field vector on that side is coming out of the page (middle finger pointing toward you), and holding your right hand in that manner points your thumb to the left.

For simple DC circuits and circuit elements, Poynting's theory of power transfer may seem like a mere curiosity. It fails to explain anything we could not already explain using the model of potential energy gained and lost by mobile charge carriers, and it requires contortions of your right hand to properly align all the vectors. However, in some applications such as *radio* where energy radiates away from structures called *antennas* in the form of electromagnetic waves (oscillating electric and magnetic fields), Poynting's theory is the *only* suitable explanation for power transfer because there are no wires to convey mobile electric charges from source (transmitting antenna) to load (receiving antenna). Below we see a simplified representation of an electromagnetic wave consisting of two oscillating fields (shown here as an electric field oscillating vertically and a magnetic field oscillating horizontally), and if you use the right-hand rule in each half-cycle you will find that the Poynting vector consistently points in the same direction at the speed of light:



Based on the direction of the Poynting vector we see in this illustration, the source (transmitting antenna) would be located somewhere above and to the left of the drawn wave. There is no definite location for a load, as electromagnetic waves spread out in *all directions* away from the source. Our simple illustration merely shows a "cross-section" of a wave radiating *cylindrically* away from the transmitting antenna. The real electromagnetic wave (of which this illustration shows just a portion) would have an electric field resembling ripples on a pond oscillating vertically while radiating away in all horizontal directions from a single point, and have a magnetic field resembling a set of concentric circles oscillating rotationally in the horizontal plane while also radiating in all directions from that same point.

4.5 Maxwell's equations of electromagnetism

The Scottish physicist James Clerk Maxwell mathematically proved the interrelationships of electric and magnetic fields, publishing his results in the book *A Treatise on Electricity and Magnetism* in 1873. His equations were later simplified and consolidated by the work of Oliver Heaviside, commonly expressed in the following forms describing electric fields (**E**) and magnetic fields (**B**) within a vacuum:

$$\oint \mathbf{E} \cdot d\mathbf{A} = \frac{Q}{\epsilon_0}$$

$$\oint \mathbf{B} \cdot d\mathbf{A} = 0$$

$$\oint \mathbf{E} \cdot d\mathbf{s} = -\frac{d\Phi_B}{dt}$$

$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 I + \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$$

We will now explore each of these four equations, relating them to laws codified by other early electrical researchers, as well as describe how they relate to the phenomenon of *electromagnetic waves*.

4.5.1 Gauss's Law of electric fields

$$\oint \mathbf{E} \cdot d\mathbf{A} = \frac{Q}{\epsilon_0}$$

The first of these equations simply describes electric fields as spreading out from a quantity of electric charge (Q). If we imagine a three-dimensional surface completely enclosing an electric charge (e.g. a soap bubble surrounding a charge), the total quantity of electric flux passing through that surface will be the product of the electric field (also known as the electric flux density, **E**) and the enclosing area (**A**). This is also known as *Gauss's Law of electric fields*.

4.5.2 Gauss's Law of magnetic fields

$$\oint \mathbf{B} \cdot d\mathbf{A} = 0$$

The second of these equations describes magnetic fields passing through a three-dimensional enclosing surface. If we imagine a magnet completely enclosed within a soap bubble, the sum total of magnetic flux passing out through that soap bubble's surface must equal the sum total of magnetic flux re-entering it somewhere else. Literally, this equation says the product of magnetic field (also known as magnetic flux density **B**) and the enclosing area (**A**) must be algebraically equal to zero. This is to say, magnetic fields must always exist as *closed loops*, or alternatively we may say there is no such thing as a magnetic monopole (i.e. a solitary North or South pole without its complement, or a *magnetic charge*). In this way magnetic fields are quite different from electric fields which radiate away from discrete electric charges without ever returning. This is also known as *Gauss's Law of magnetic fields*.

4.5.3 Faraday's Law of electromagnetic induction, extended

$$\oint \mathbf{E} \cdot d\mathbf{s} = -\frac{d\Phi_B}{dt}$$

The third equation states that an electric field ($\mathbf{E}$) will be produced in open space by a varying magnetic flux $\left(\frac{d\Phi_B}{dt}\right)$. Michael Faraday expressed this phenomenon in terms of voltage induced along the length of a conductor by a time-varying magnetic field, but Maxwell demonstrated mathematically that this same thing happens even in empty space!

4.5.4 Ampère's Circuital Law, extended

$$\oint \mathbf{B} \cdot d\mathbf{s} = \mu_0 I + \mu_0 \epsilon_0 \frac{d\Phi_E}{dt}$$

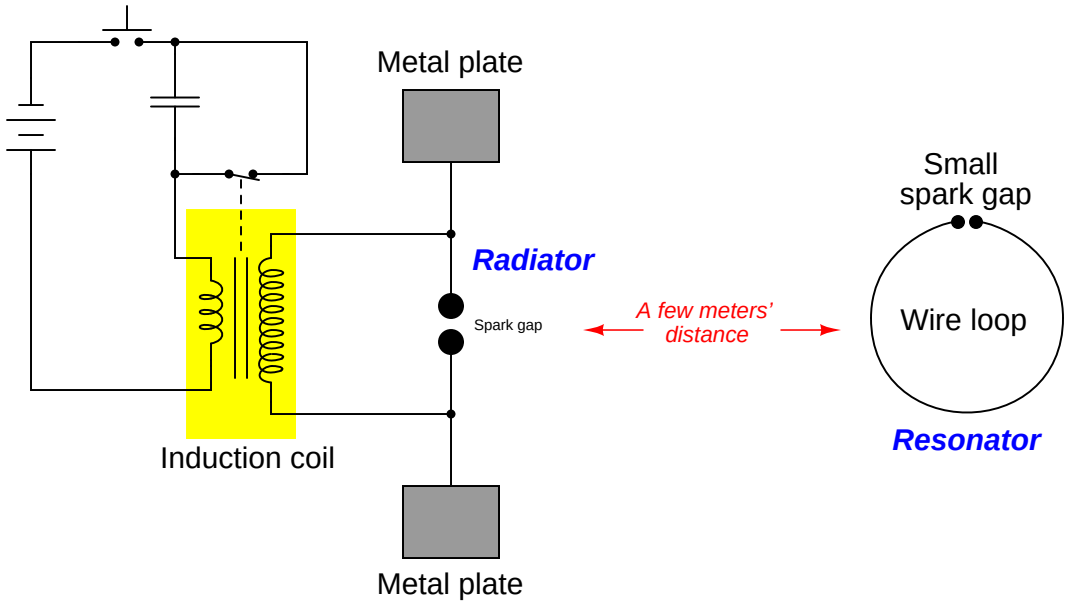
The fourth equation states than a magnetic field ($\mathbf{B}$) will be produced in open space either by an electric current (I) and/or by a varying electric flux $\left(\frac{d\Phi_E}{dt}\right)$. The French scientist André-Marie Ampère described the relationship between current passing through a conductor and the magnetic field created around that conductor by the current, but once again Maxwell extended this concept to include magnetic fields generated in empty space. In empty space, where there are no moving electric charges (i.e. current, I) to generate a magnetic field, only the second term of the equation applies with a time-varying electric field substituting for actual electric current.

4.5.5 Proof of electromagnetic waves

Given the complementary relationship between time-varying electric and magnetic fields, Maxwell reasoned, it was possible for a varying electric field to create a varying magnetic field which would then create another varying electric field, and so on. This cause-and-effect cycle could continue, ad infinitum, with fast-changing electric and magnetic fields radiating off into open space without needing wires to carry or guide them, or a tank circuit to sustain the oscillations. In other words, *these complementary fields self-sustain as they travel*, although they do become weaker due to their spreading out of a finite amount of energy over larger and larger volumes of space.

The Prussian Academy of Science offered a reward to anyone who could experimentally validate Maxwell's prediction, and this challenge was answered by Professor Heinrich Hertz at the Engineering College in Karlsruhe, Germany in 1887, eight years after Maxwell's death. Hertz constructed and tested a pair of devices: a "radiator" to produce the electromagnetic waves, and a "resonator" to receive them.

A simplified diagram showing Hertz's experimental device is shown here:



An "induction coil" (a buzzing device constructed of a self-interrupting relay and step-up transformer winding to generate a continuous pulsing waveform of high voltage) provided an extremely noisy (i.e. harmonically rich)[13] AC signal to the radiator, while a spark gap at the

[13] A fundamental property of waves is that any wave-shape, no matter how complex, is mathematically equivalent to a series of perfectly sinusoidal waves of differing frequencies added together. Waveforms with fast rise/fall times, such as the pulse waveforms produced by switched induction coils, contain many such high-frequency "harmonic" signals, and it is these high-frequency signals that created the radiated electromagnetic waves in Hertz's experiments. The induction coil's secondary winding inductance combined with the parasitic capacitance of the radiator's wires and plates provided the means to momentarily sustain some of these high-frequency oscillations long enough to sustain visible sparks at the resonator's gap.

resonator provided indication that the electromagnetic waves were captured and converted into voltage by the resonator wire.

Both the radiator and the resonator are antennas. The purpose of the transmitting antenna (radiator) is to take high-frequency AC power and radiate that power in the form of electromagnetic waves: self-sustaining electric and magnetic fields propagating outward into open space. The purpose of the receiving antenna is to capture those electromagnetic waves and convert them into an electrical signal (i.e. AC voltage and current). All antennas – from historical to the most modern – behave in fundamentally the same way: energize them with high-frequency AC electrical power, and they will radiate electromagnetic waves at that frequency; expose them to electromagnetic waves, and they will produce a very small AC electrical signal at the same frequency as the incident radiation.

4.6 Common coaxial cable types

The following table lists several different types of coaxial cable commonly found in electronic systems. Exact specifications do vary from manufacturer to manufacturer, so check datasheets if you need to be precise!

Characteristic impedance (Z) is expressed in Ohms, and does not vary with cable length, signal frequency, or signal power. Maximum power handling capacity is constant for all cable lengths but does decrease with increasing frequency, the figures in this table assuming a signal frequency of 100 MHz. Dissipative losses are mostly due to dielectric heating of the plastic insulation separating the center conductor from the shield, and increases with increasing frequency. These losses are specified in decibels per 100 feet of cable length, for a signal frequency of 100 MHz. Propagation velocity factor ($\frac{v}{c}$) is the ratio of the signal's propagation velocity compared to the speed of light in a vacuum, and is constant for all cable lengths and signal frequencies, mostly affected by the chemical composition of the plastic insulation separating the center conductor from the shield.

Type	$Z\ \Omega$	**Loss**	**Max. power**	**O.D.**	$\frac{v}{c}$
RG-6	75	−2.9 dB	n/a	0.332 in	0.66
RG-8	50	−1.4 dB	1150 W	0.405 in	0.82
RG-11	75	−2.0 dB	n/a	0.405 in	0.66
RG-58	50	−4.3 dB	542 W	0.159 in	0.70
RG-59	75	−3.0 dB	n/a	0.305 in	0.66
RG-213	50	−1.9 dB	750 W	0.405 in	0.66
RG-174	50	−8.4 dB	161 W	0.110 in	0.66
LMR-100	50	−6.4 dB	140 W	0.110 in	0.66
LMR-200	50	−3.2 dB	550 W	0.195 in	0.83
LMR-400	50	−1.3 dB	1800 W	0.405 in	0.85
LMR-600	50	−0.8 dB	2960 W	0.590 in	0.87

"RG" is an old military designation meaning "Radio Guide", while "LMR" is a trademark of Times Microwave Systems and represents a new set of modern coaxial cable specifications intended to supersede some of the older RG styles, LMR-100 being an improvement over RG-174, LMR-200 being an improvement over RG-58, and LMR-400 being an improvement over RG-8. LMR-600 type cable is an entirely new standard.

Note that RG-6 and RG-59 coaxial cable is intended for low-power signal usage and therefore these cables are often unspecified in terms of power handling.

Chapter 5

Animations

Some concepts are much easier to grasp when seen in *action*. A simple yet effective form of animation suitable to an electronic document such as this is a "flip-book" animation where a set of pages in the document show successive frames of a simple animation. Such "flip-book" animations are designed to be viewed by paging forward (and/or back) with the document-reading software application, watching it frame-by-frame. Unlike video which may be difficult to pause at certain moments, "flip-book" animations lend themselves very well to individual frame viewing.

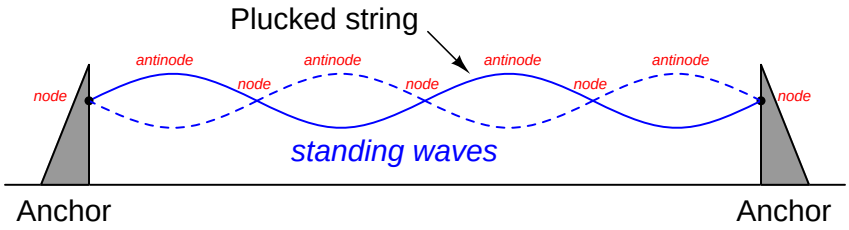
5.1 Animation of a standing wave with full reflection

This series of animations shows waveforms traveling along a transmission line, the incident (or "forward") waveform shown in red and the reflected waveform shown in blue. It is assumed that the signal source is on the left-hand side of the graph, while the transmission line terminates on the right-hand side of the graph.

If the transmission line is terminated in such a way as to completely reflect the forward waveform at its end, the reflected wave will have the exact same amplitude as the forward wave at the line's end but negative in value. This represents the state of affairs for voltage waves at the end of a shorted transmission line, or current waves at the end of an open-ended transmission line. The concept here is that the line's termination does not permit any amplitude at that end-point (e.g. no voltage at a short, no current at an open), and so the reflected wave must perfectly cancel the forward wave at that location.

However, the really interesting phenomenon is what happens as the reflected wave travels back toward the source as the source continues to output a forward wave. These two moving sinusoids superimpose with each other to produce a resultant waveform. This resultant wave does not "travel" along the transmission line like the forward and reflected waves do, but rather "stands" in place while oscillating – what is known as a *standing wave*.

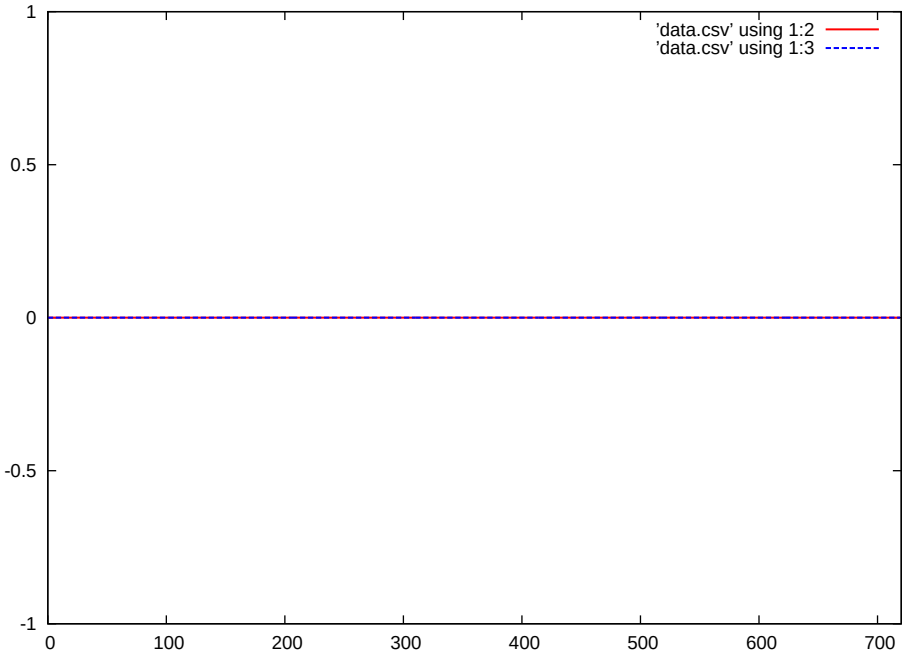
The rather non-intuitive result of standing waves is that some points along the transmission line will experience greater AC voltage than others, and some points will experience greater AC current than others. This phenomenon has many mechanical equivalents, including the existence of standing waves in plucked strings where certain points along the string's length oscillate more violently than others:



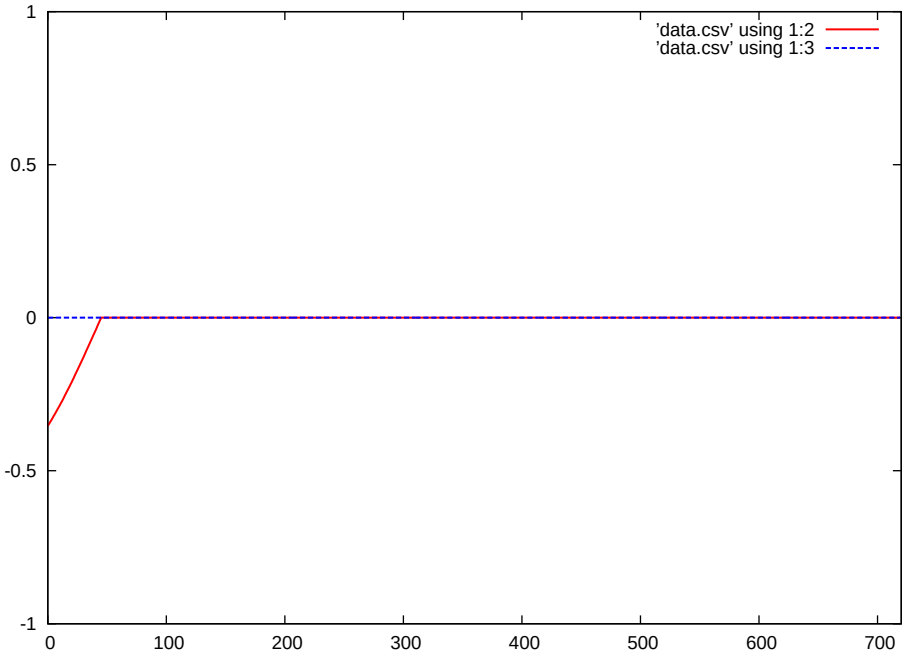
In the following flip-book animations, the first animation shows only the forward and reflected waves along the line for 1440 degrees of rotation. The second animation shows this same sequence of forward and reflected waves, but in an adjacent image shows the superposition of these two waveforms in a different color. The third animation shows that same superposition, but after the forward and reflected waves have traveled the full length of the transmission line to create an established "standing wave" along the line.

Standing wave ratio or *SWR* for any transmission line is defined as the maximum amplitude of the superposition wave divided by its minimum amplitude. In this case, where the superposition of the forward and reflected waves varies from full to zero, the SWR is infinite.

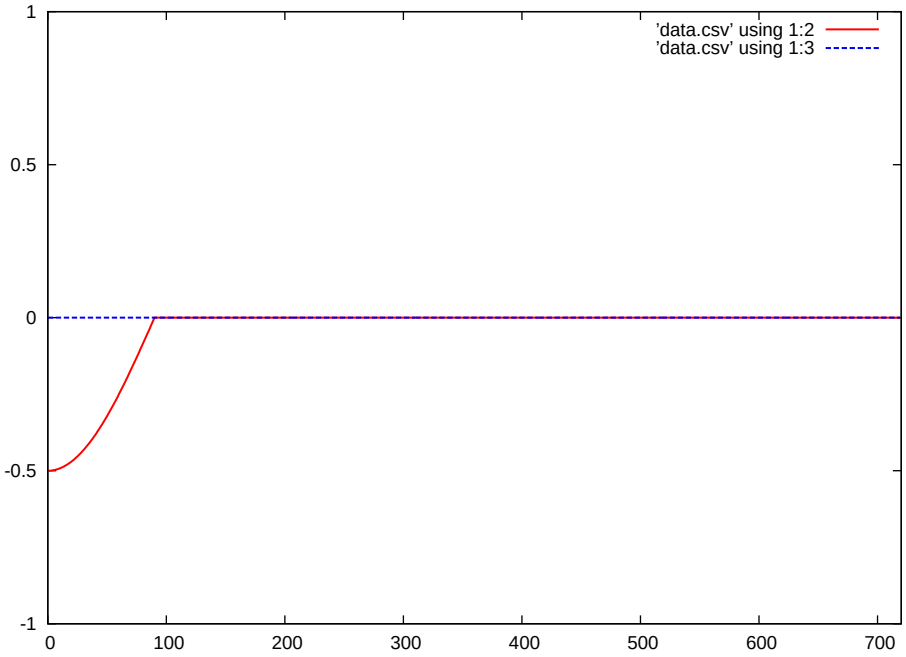
Red = forward wave Blue = reflected wave



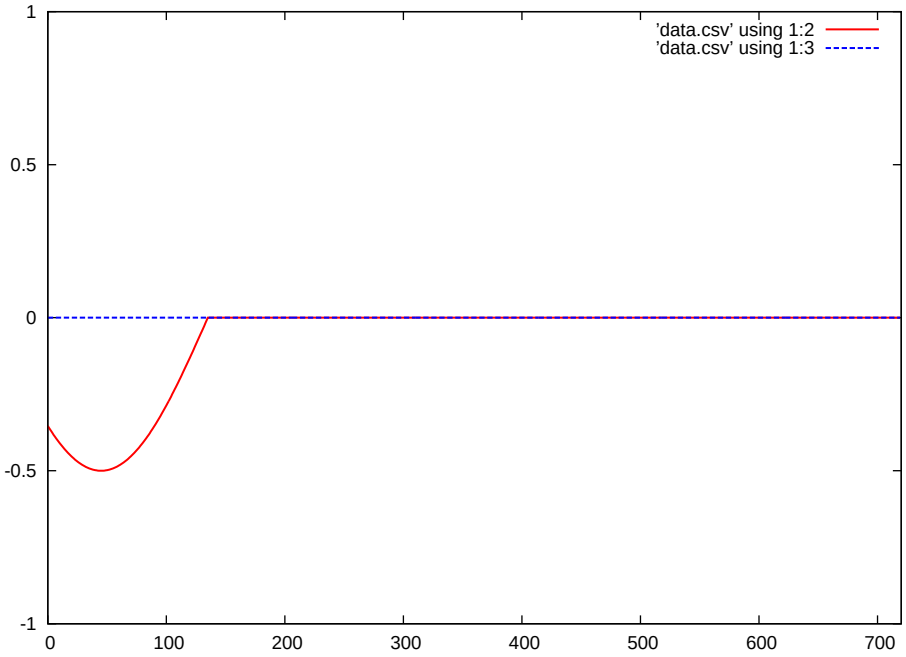
Red = forward wave Blue = reflected wave



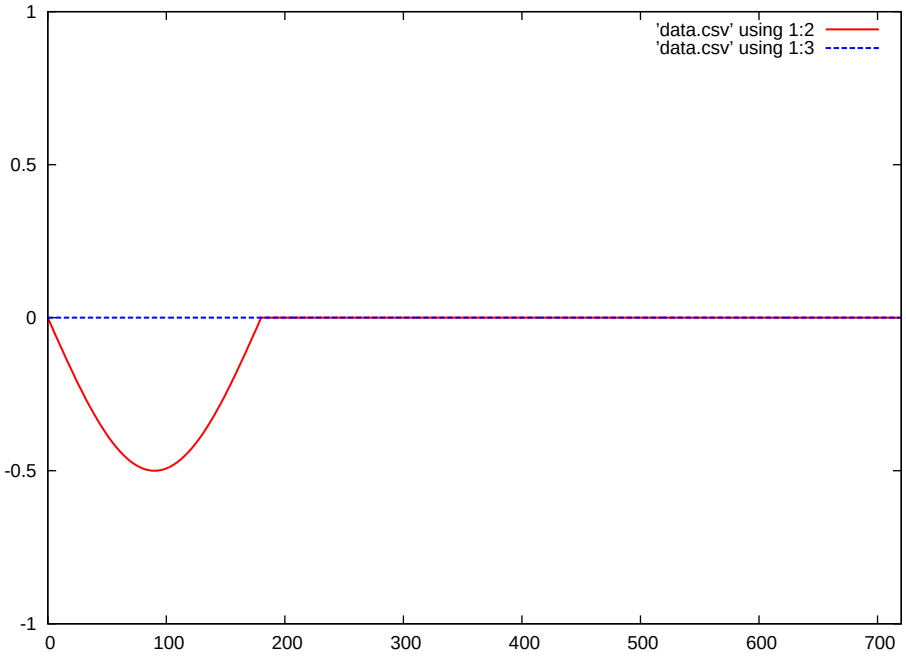
Red = forward wave Blue = reflected wave



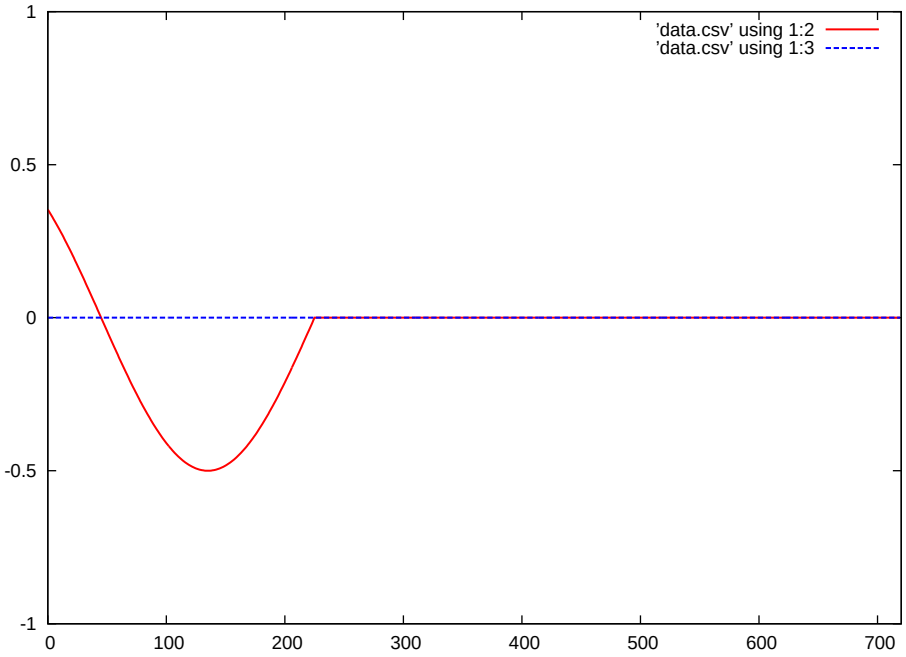
Red = forward wave Blue = reflected wave



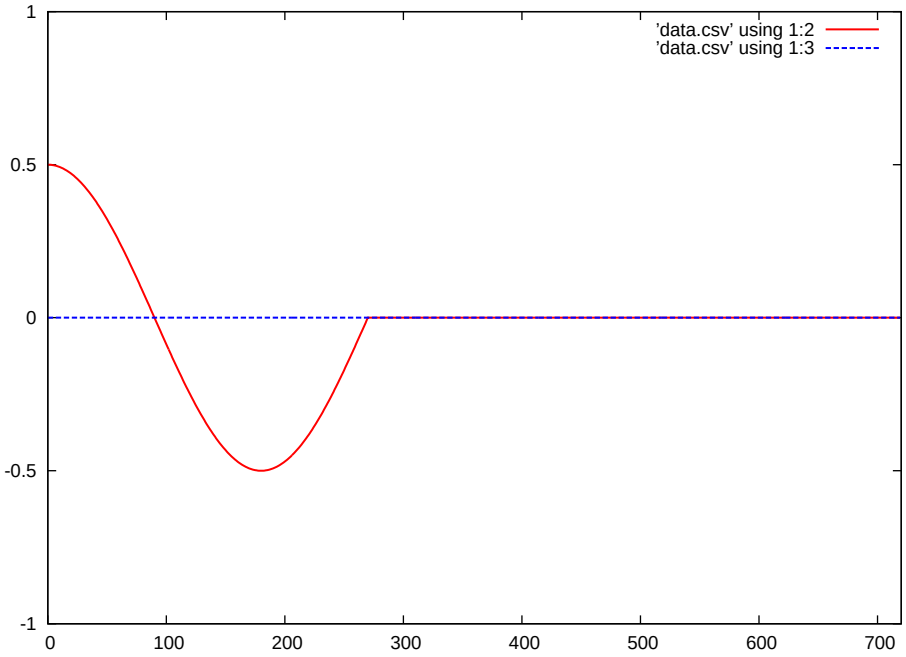
Red = forward wave Blue = reflected wave



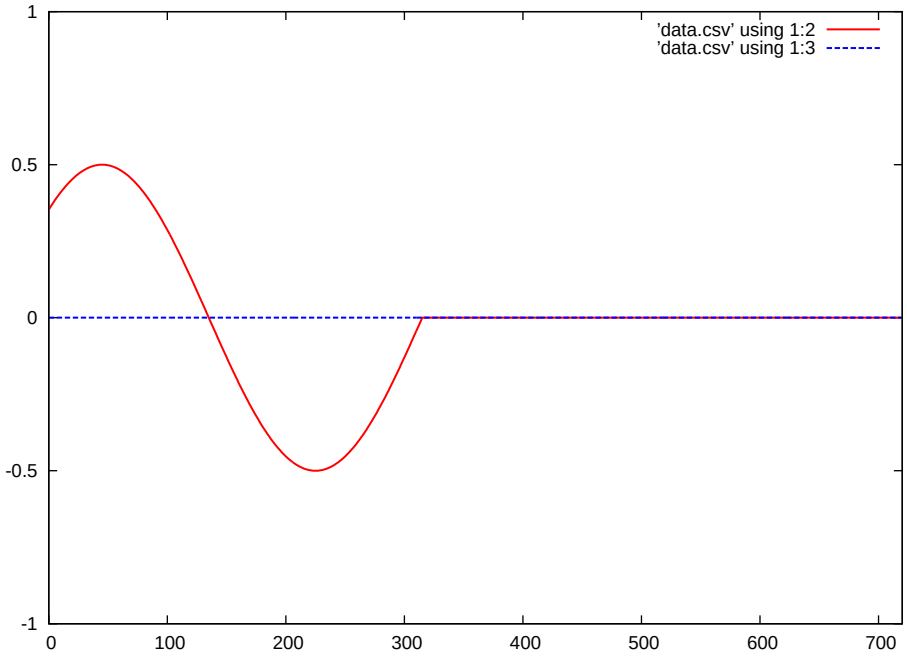
Red = forward wave Blue = reflected wave



Red = forward wave Blue = reflected wave



Red = forward wave Blue = reflected wave



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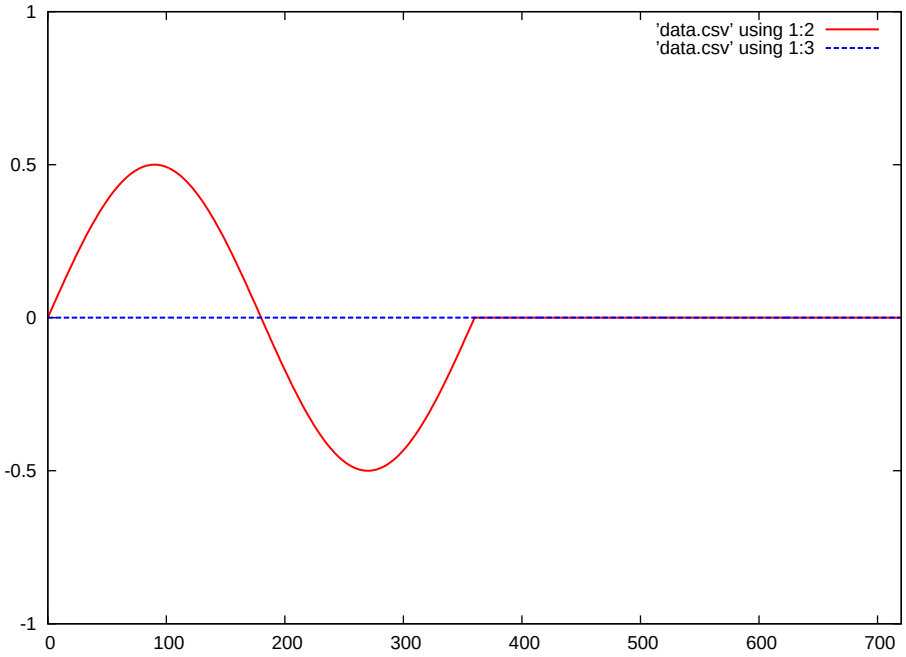
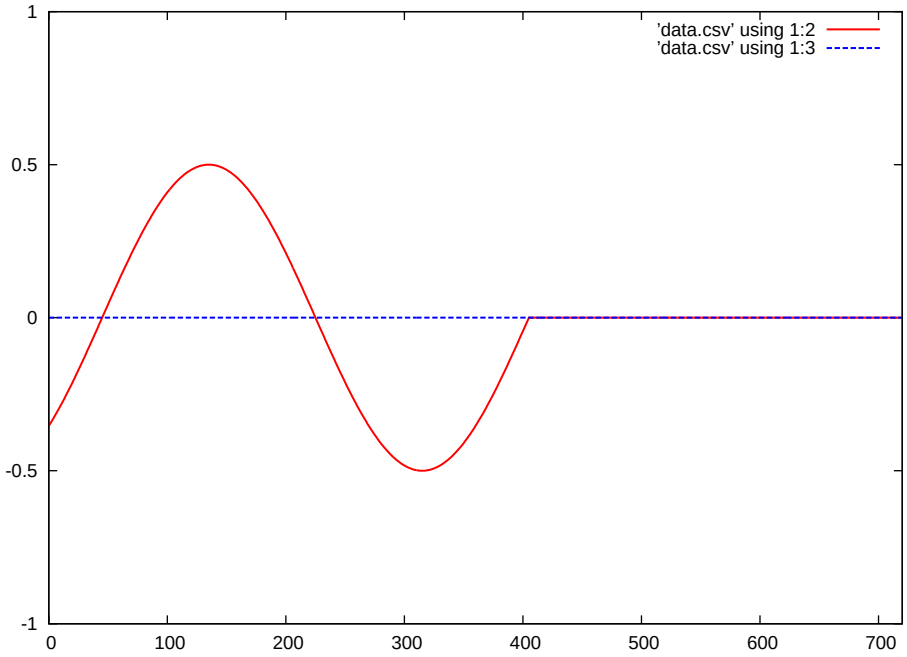
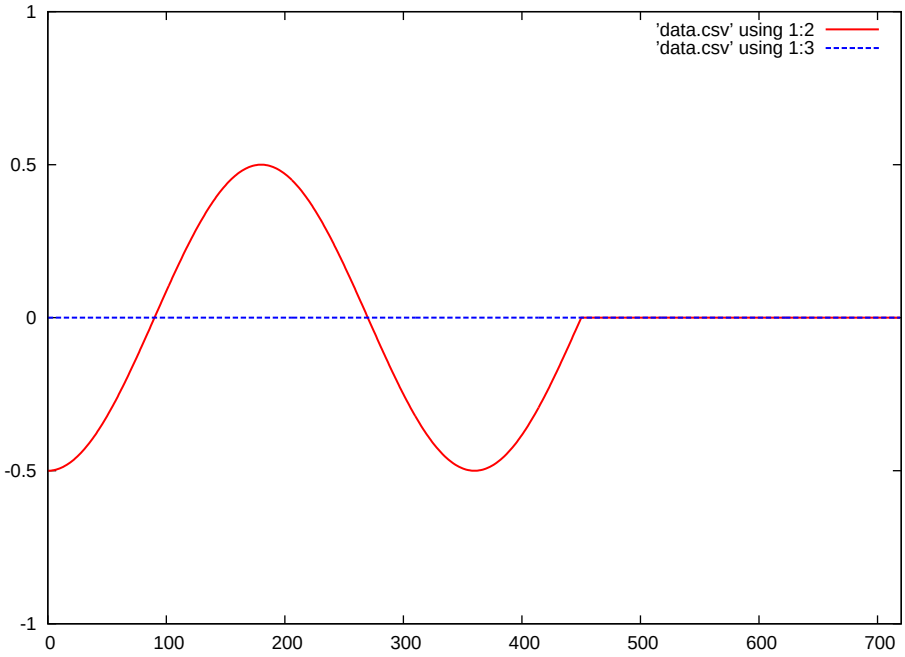


Red = forward wave Blue = reflected wave



Red = forward wave Blue = reflected wave



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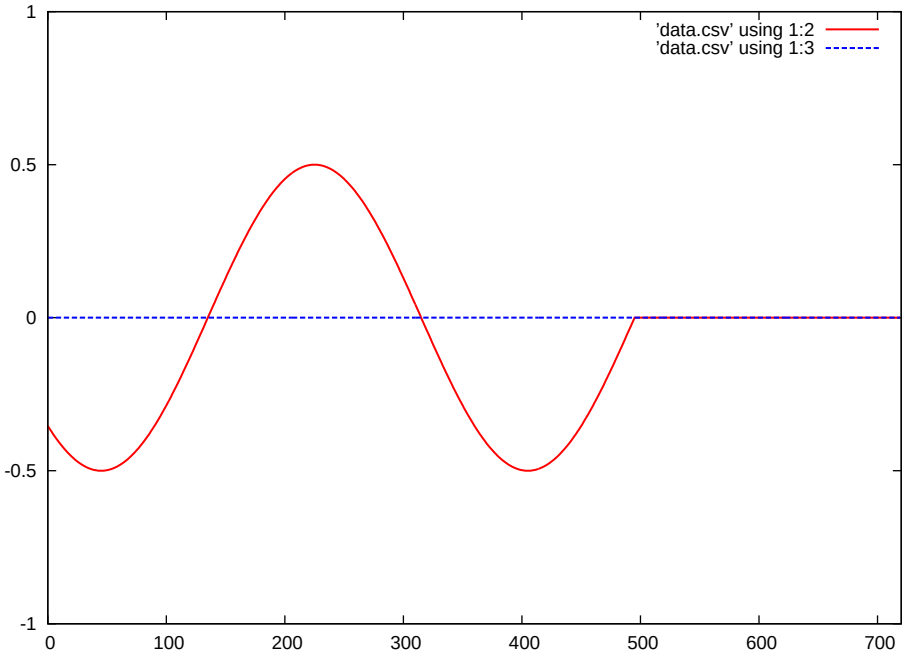

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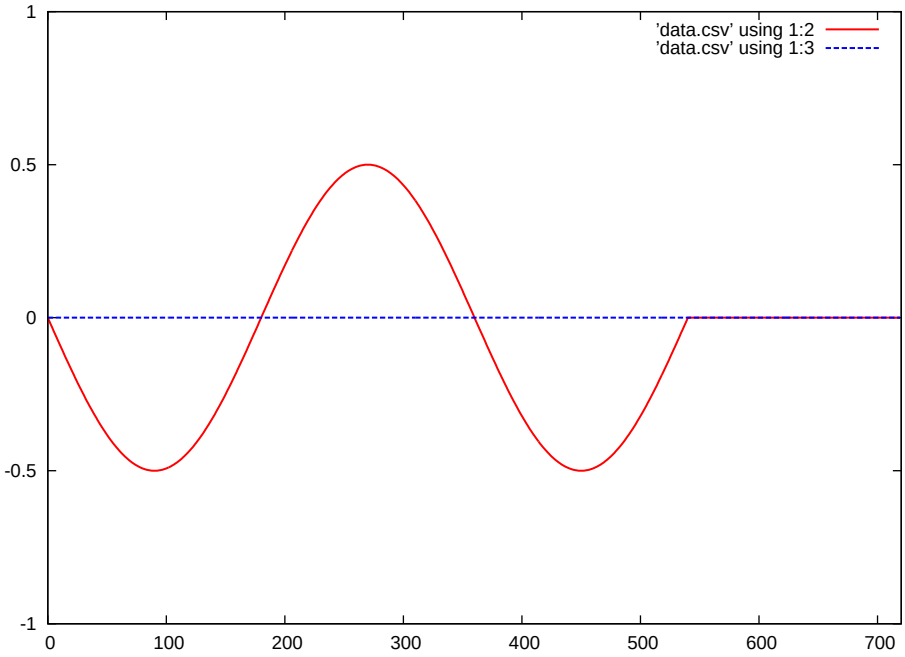
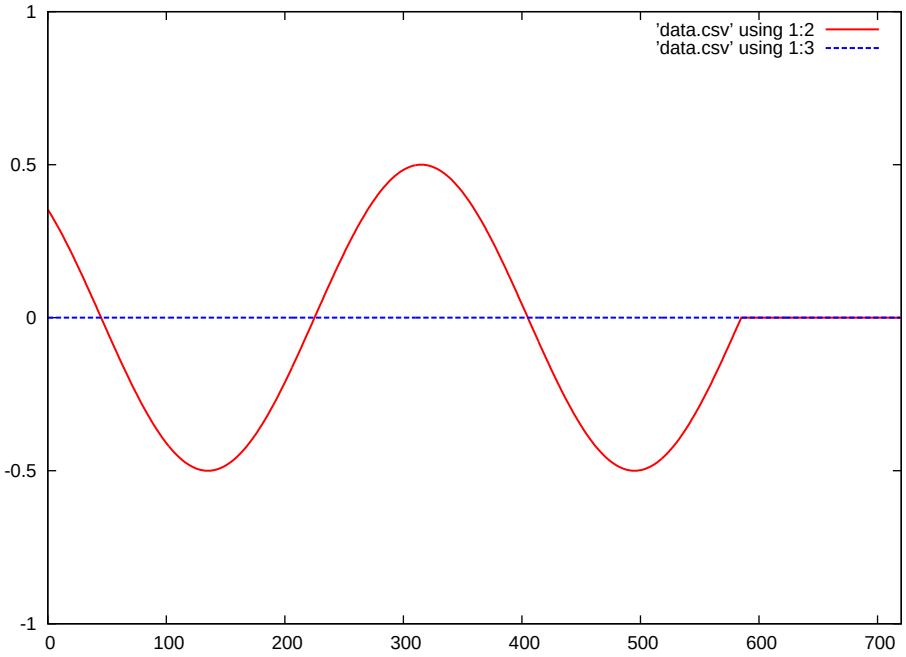


Red = forward wave Blue = reflected wave



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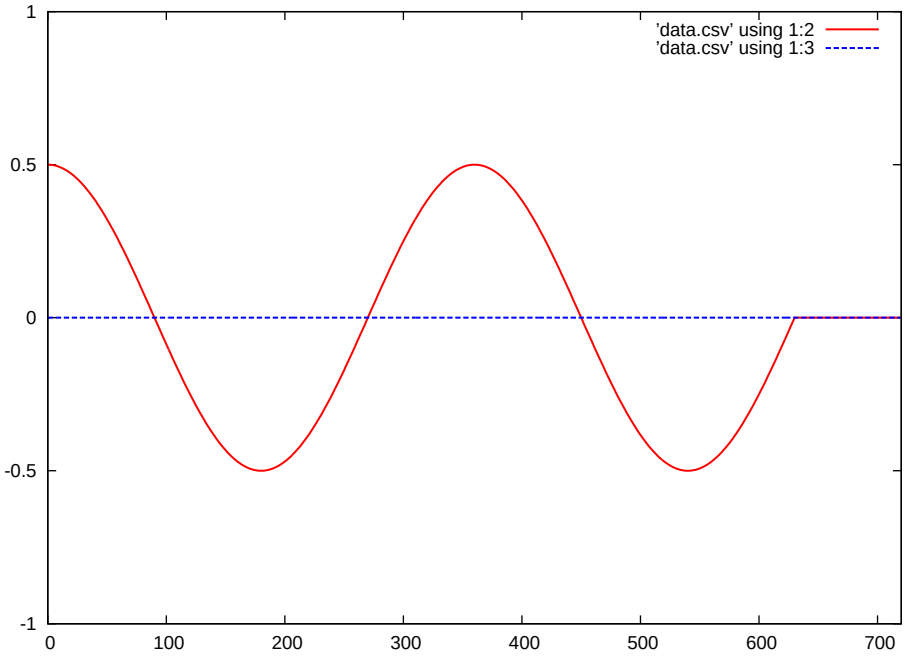

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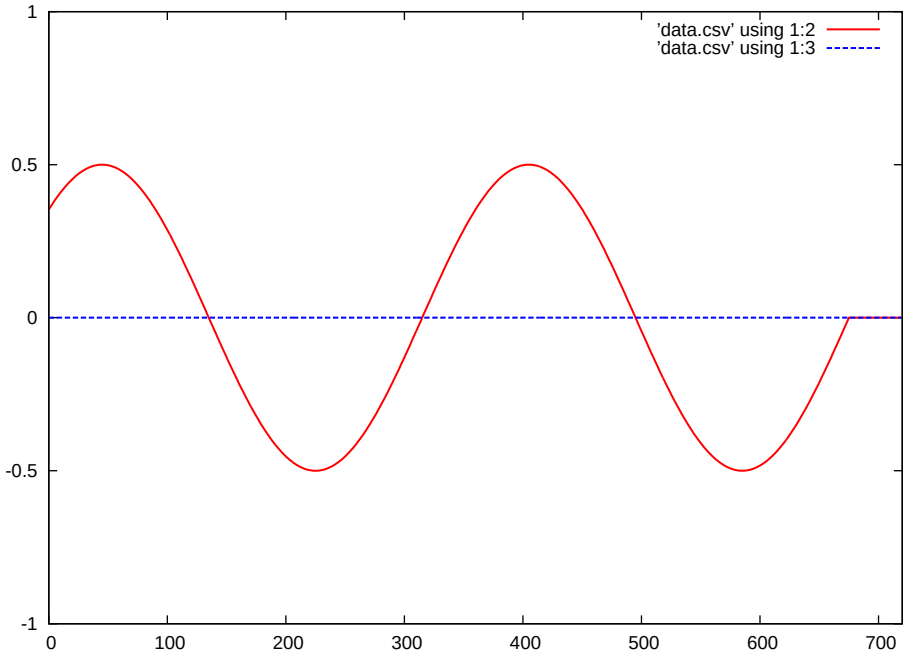

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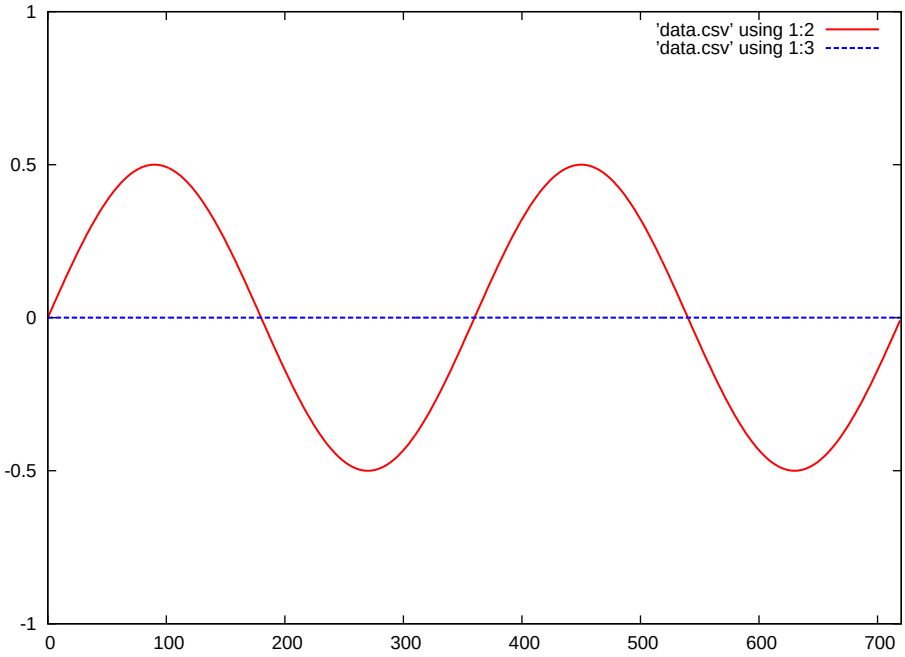

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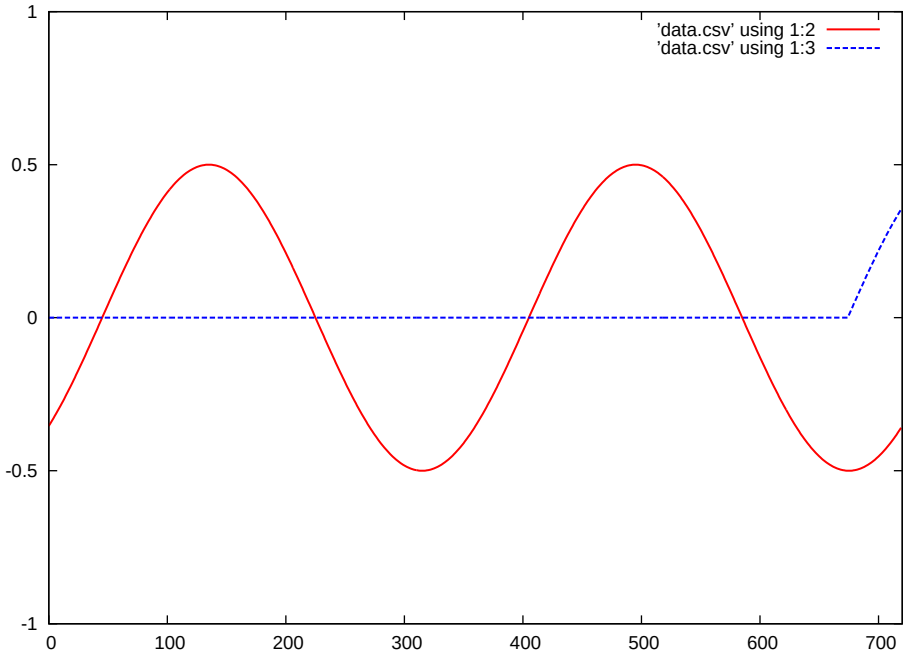

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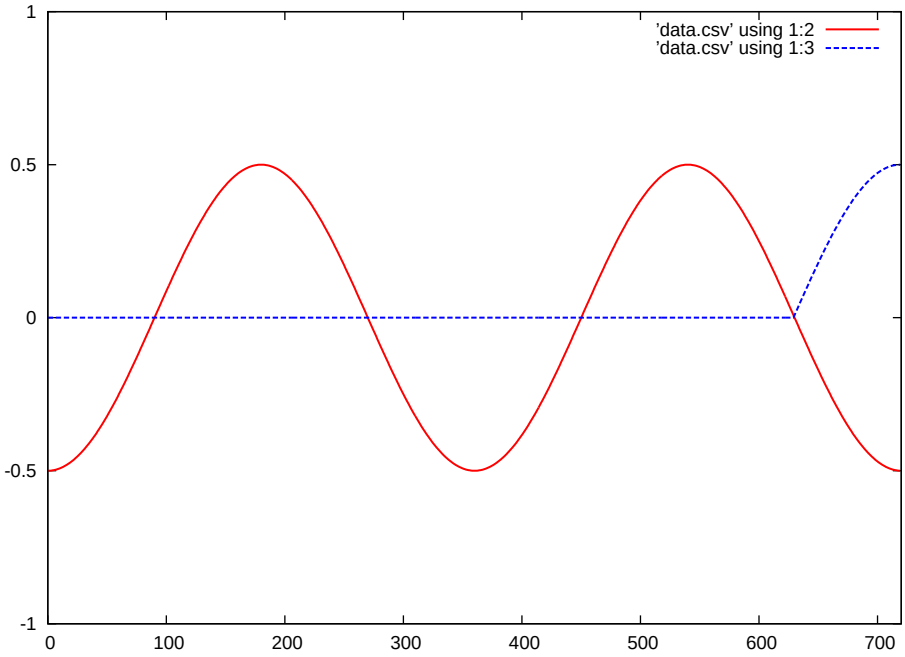

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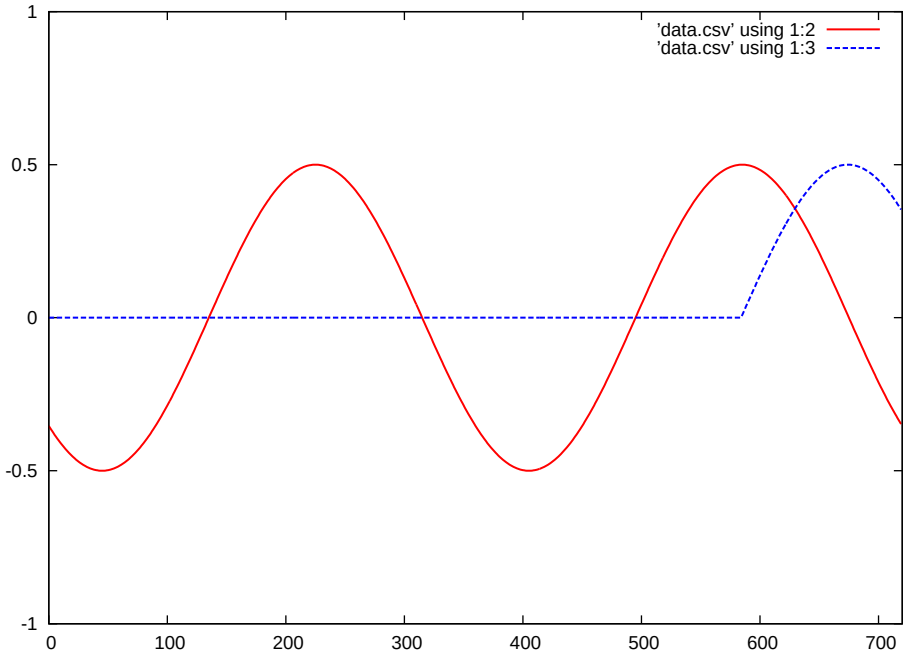

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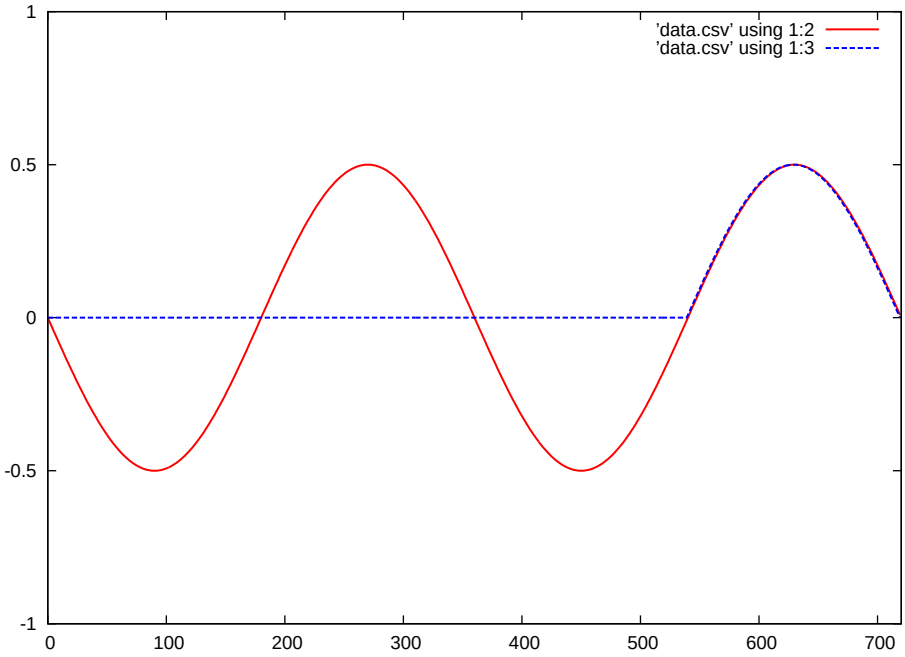

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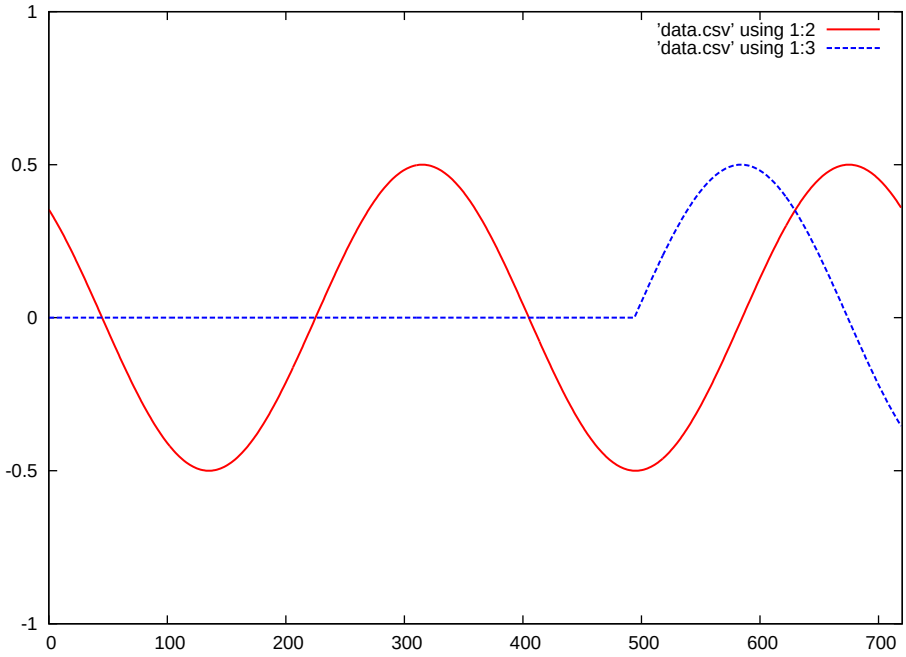
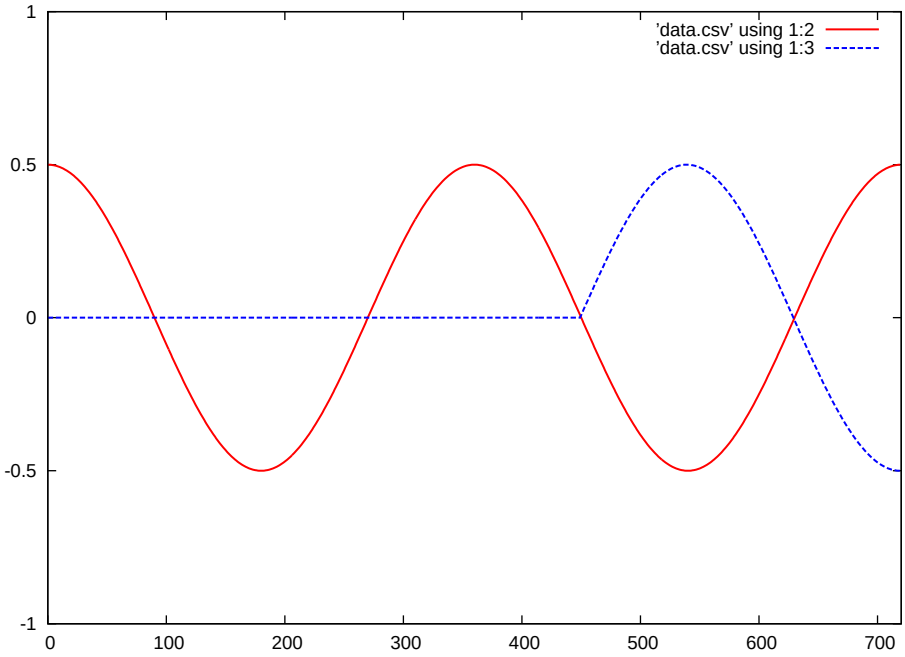


Red = forward wave Blue = reflected wave



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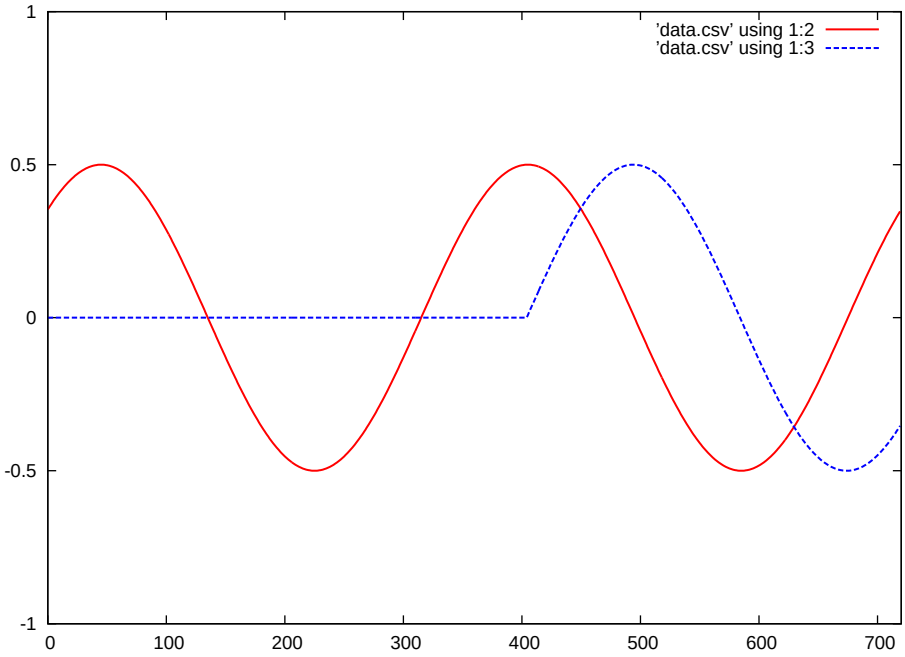

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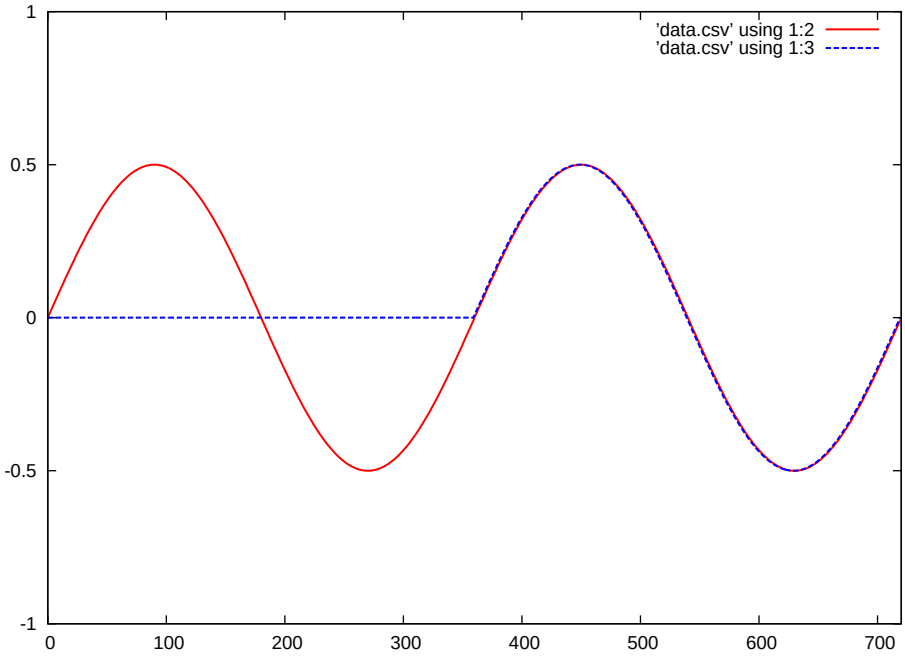
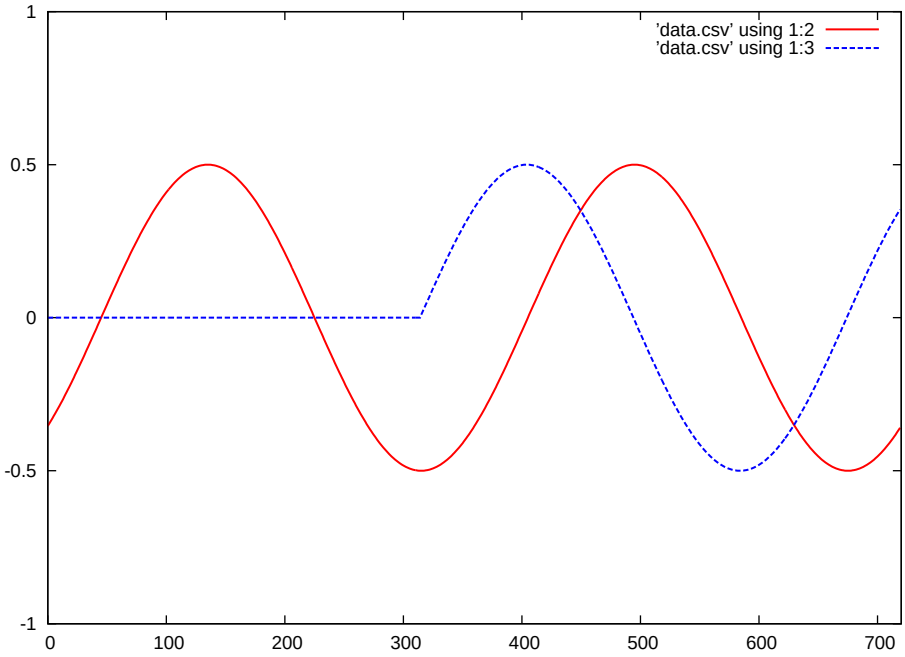


Red = forward wave Blue = reflected wave



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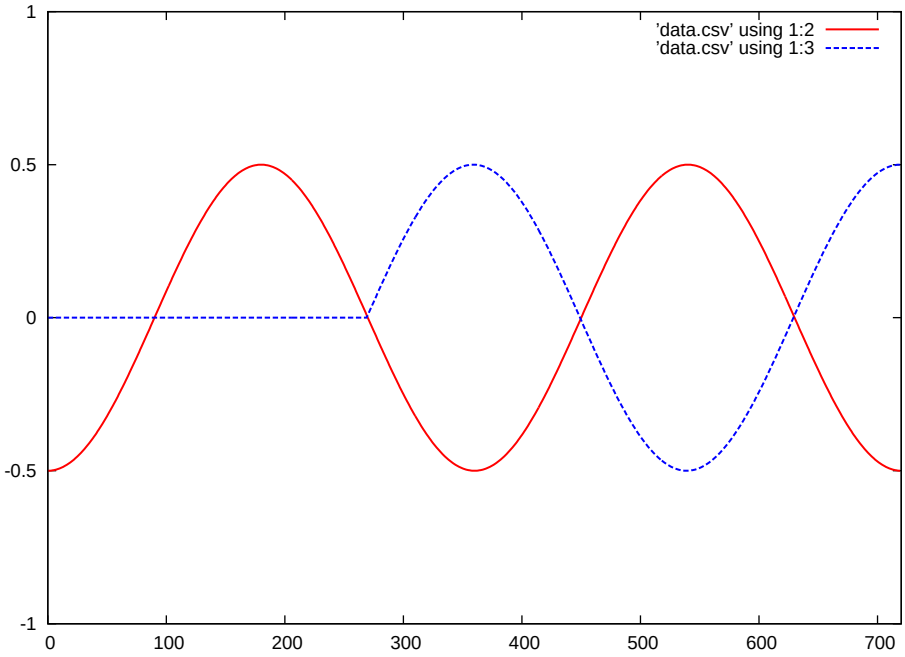

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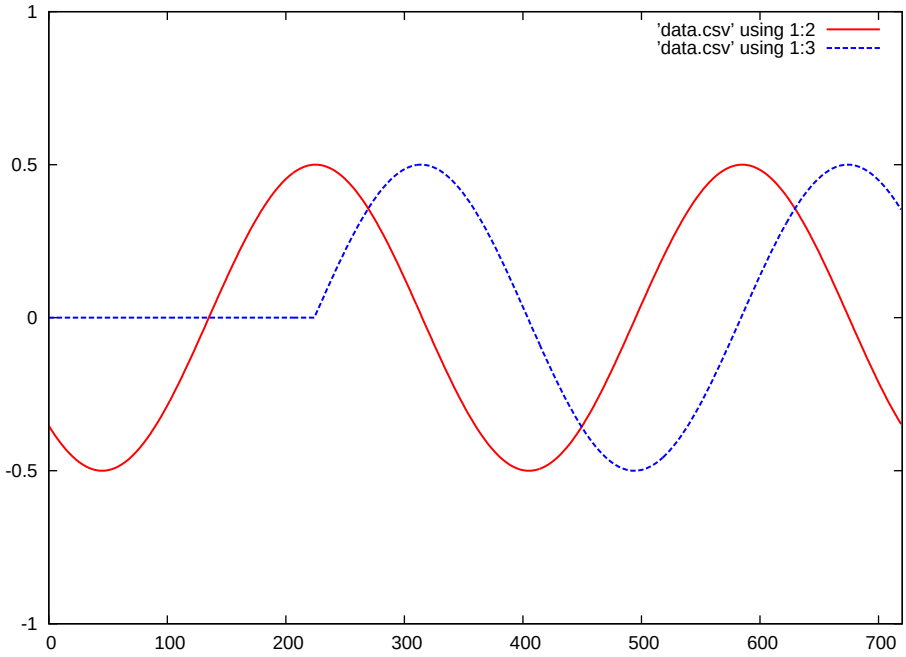

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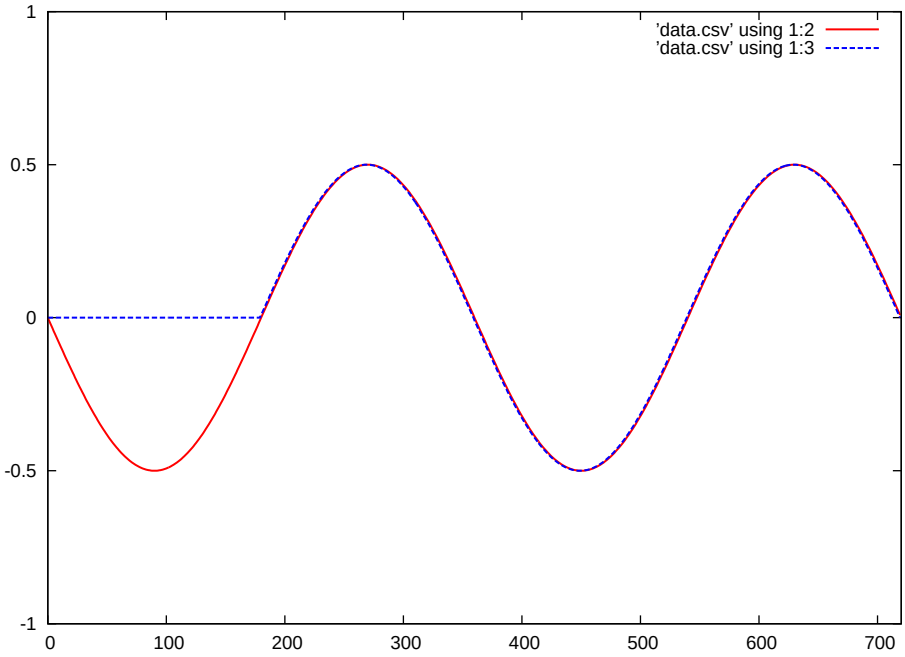

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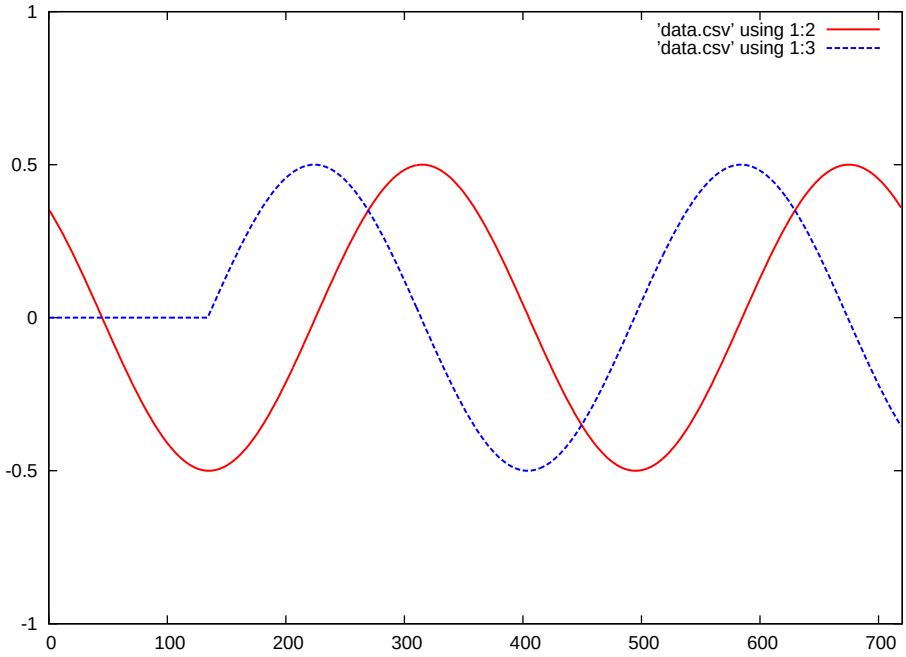

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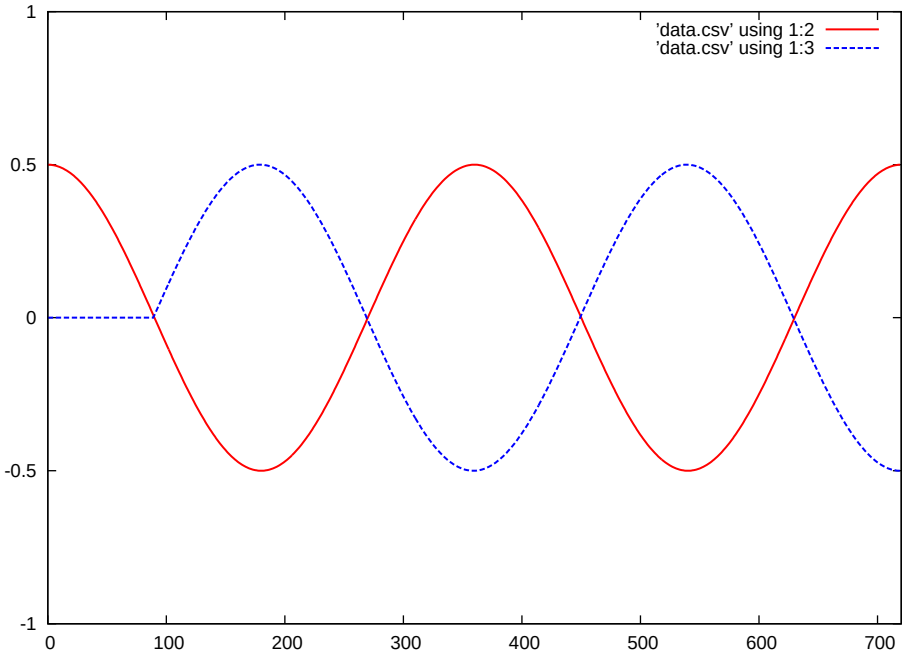

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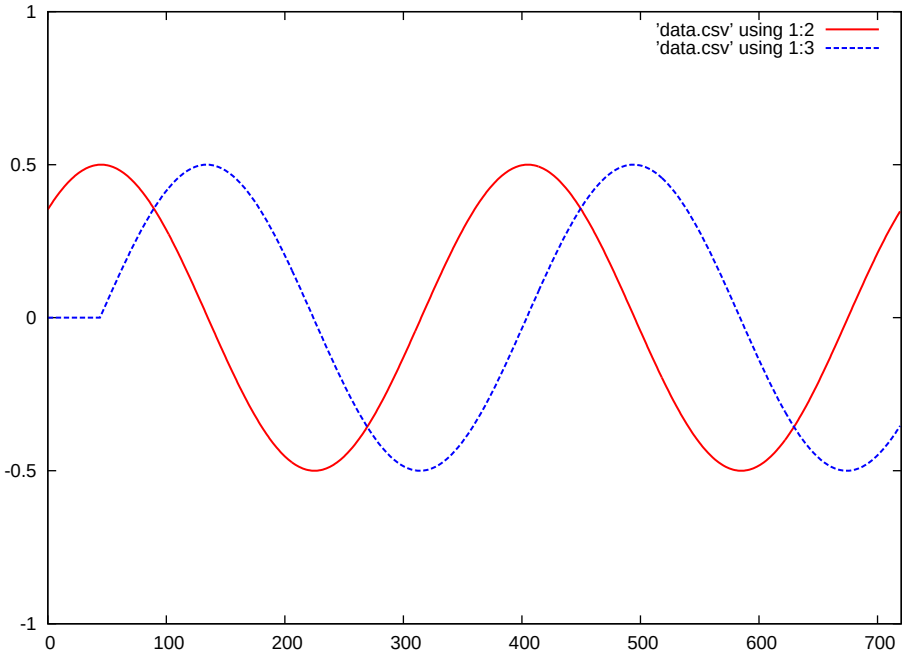
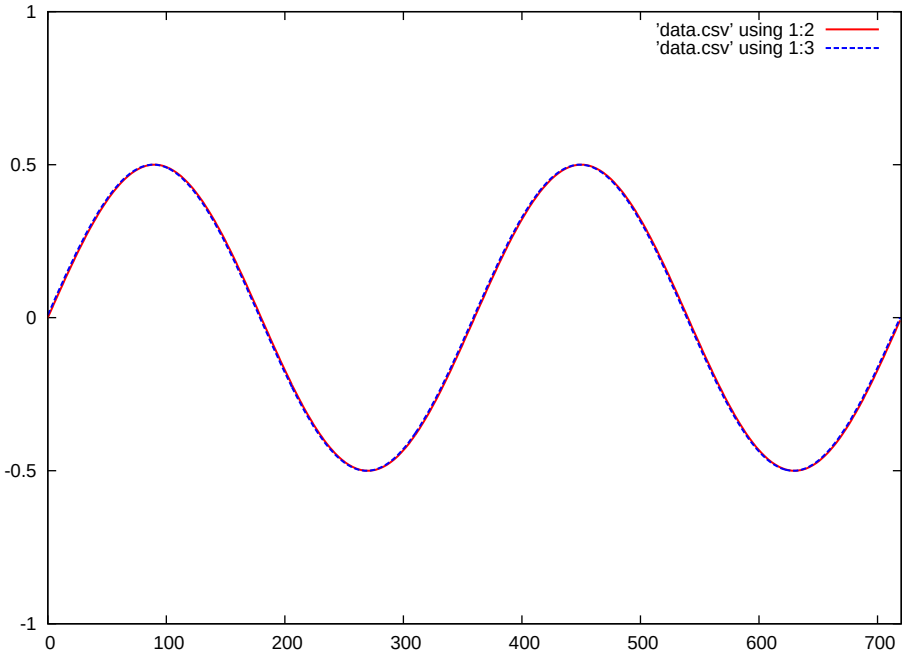
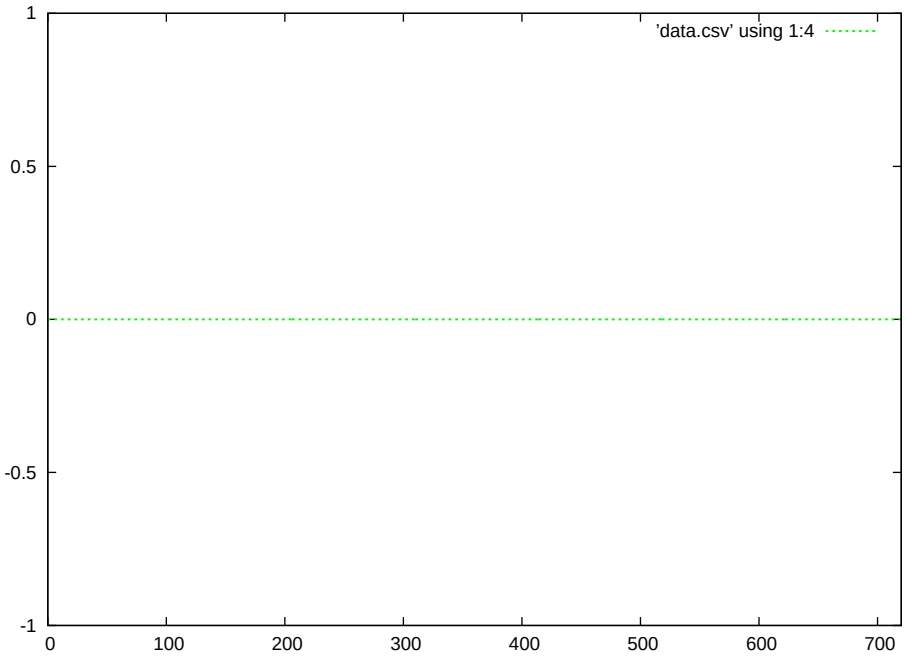


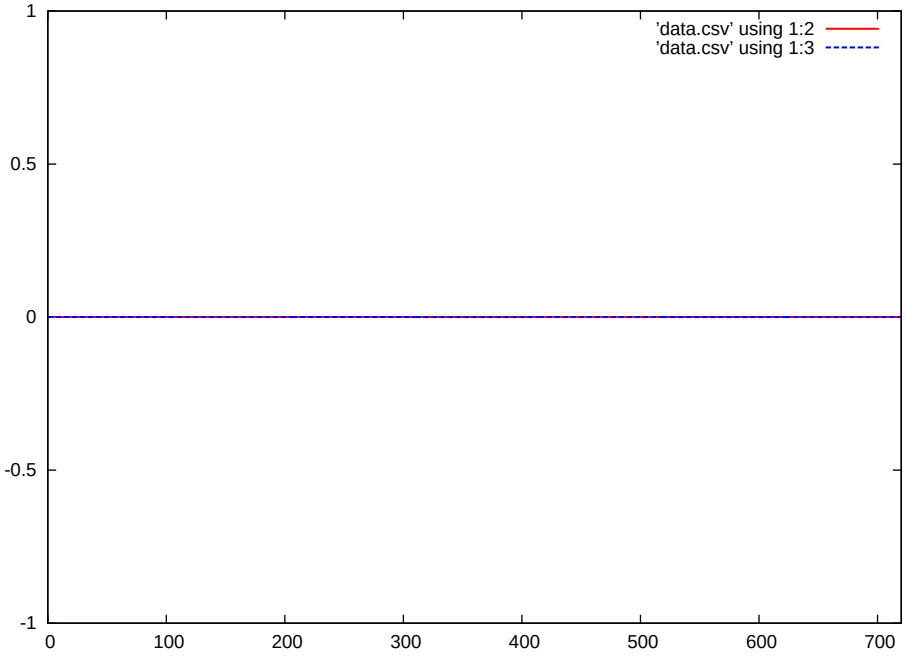
Red = forward wave Blue = reflected wave



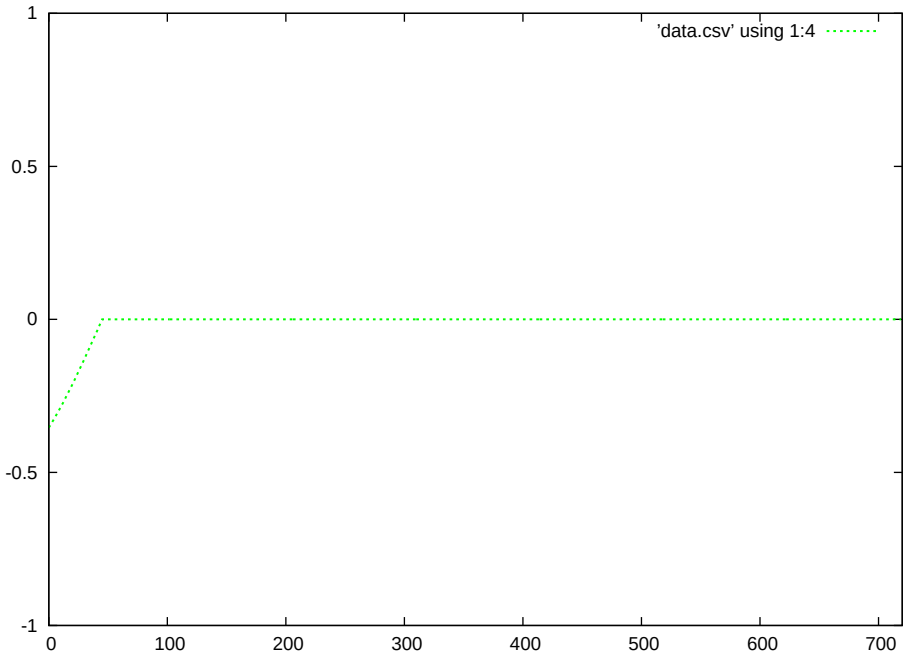
Green = superposition of the forward and reflected waves



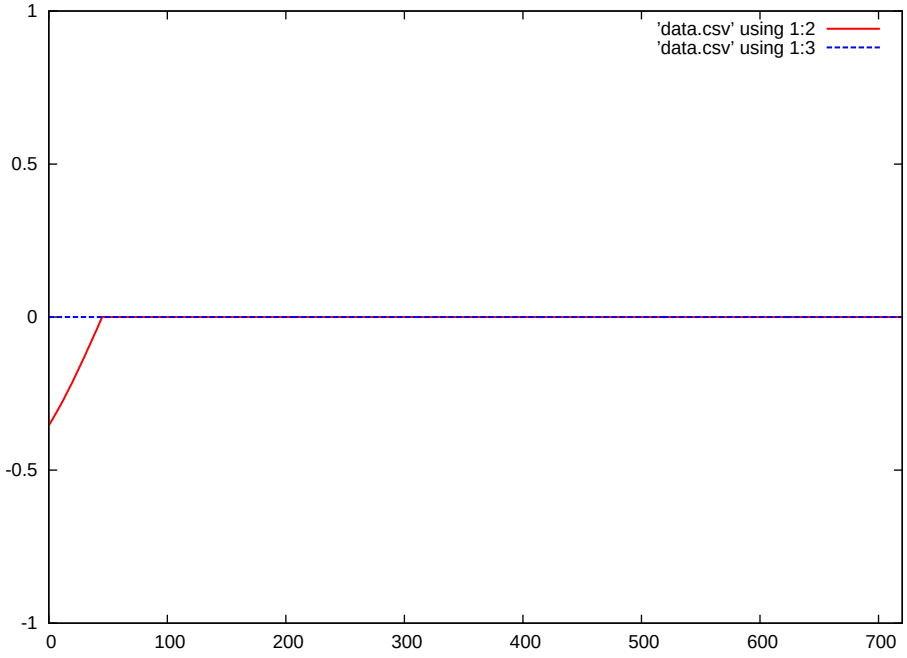
Red = forward wave Blue = reflected wave



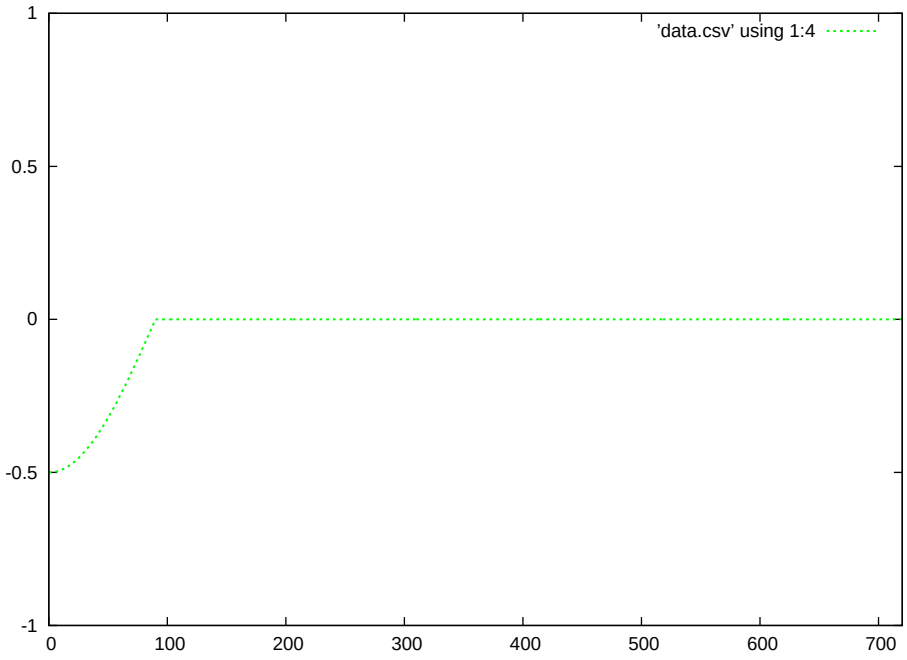
Green = superposition of the forward and reflected waves



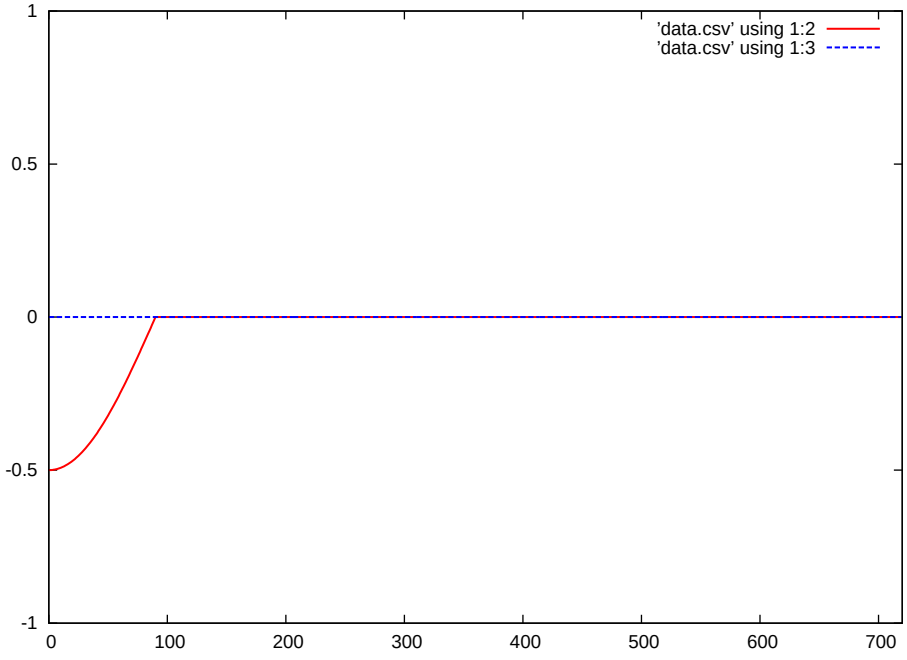
Red = forward wave Blue = reflected wave



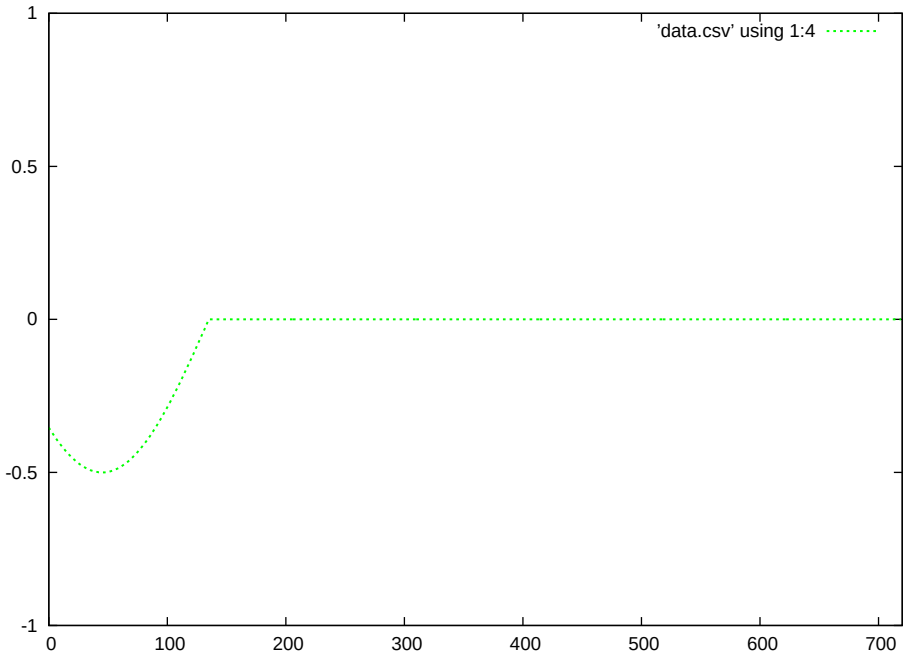
Green = superposition of the forward and reflected waves



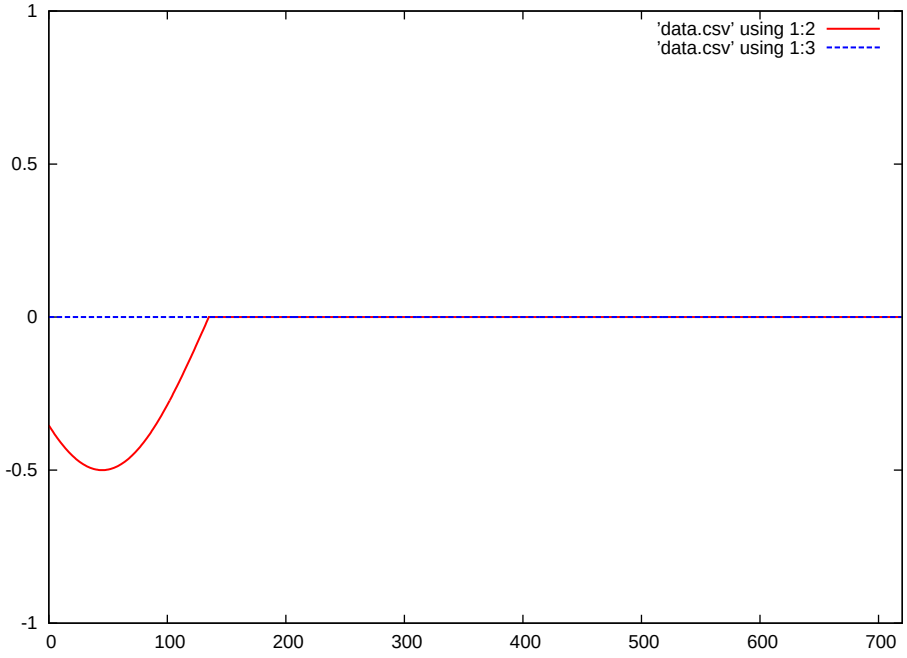
Red = forward wave Blue = reflected wave



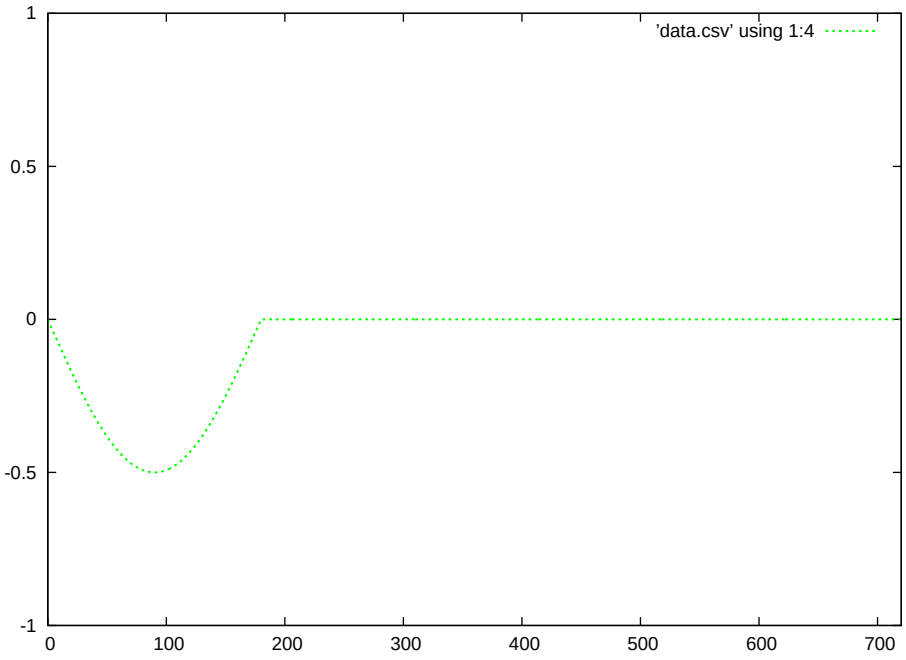
Green = superposition of the forward and reflected waves



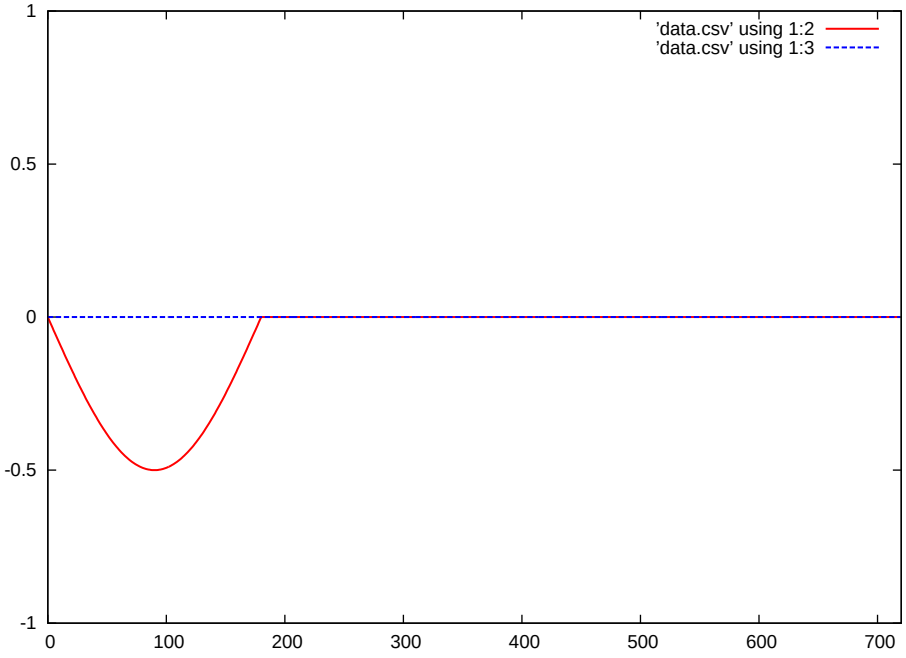
Red = forward wave Blue = reflected wave



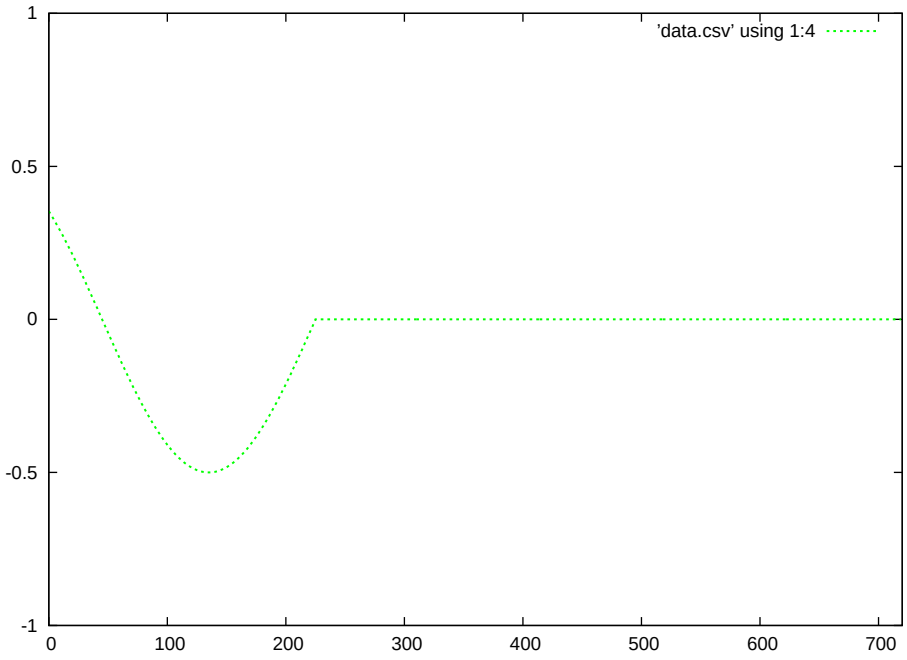
Green = superposition of the forward and reflected waves



Red = forward wave Blue = reflected wave



Green = superposition of the forward and reflected waves



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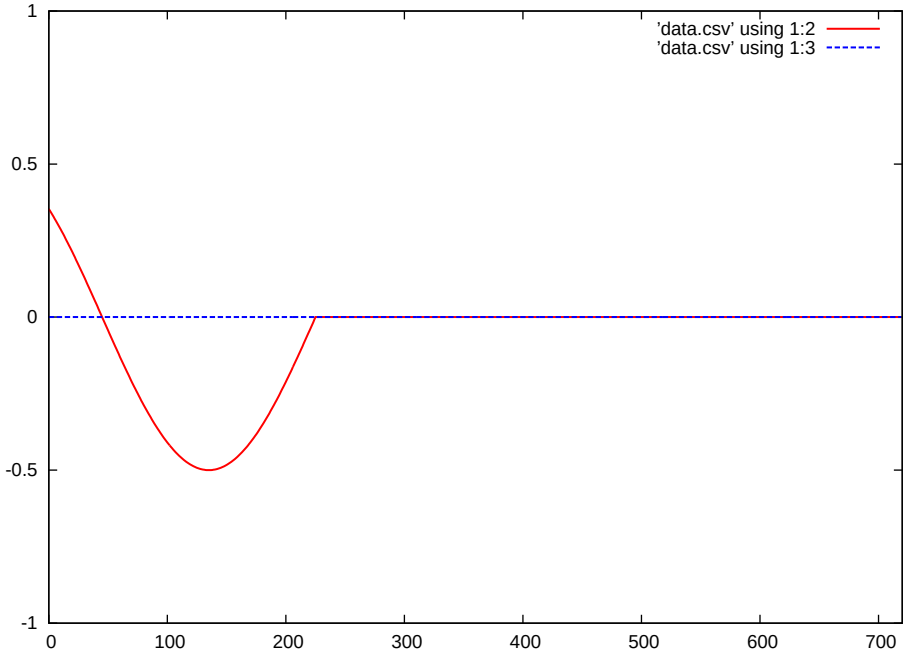

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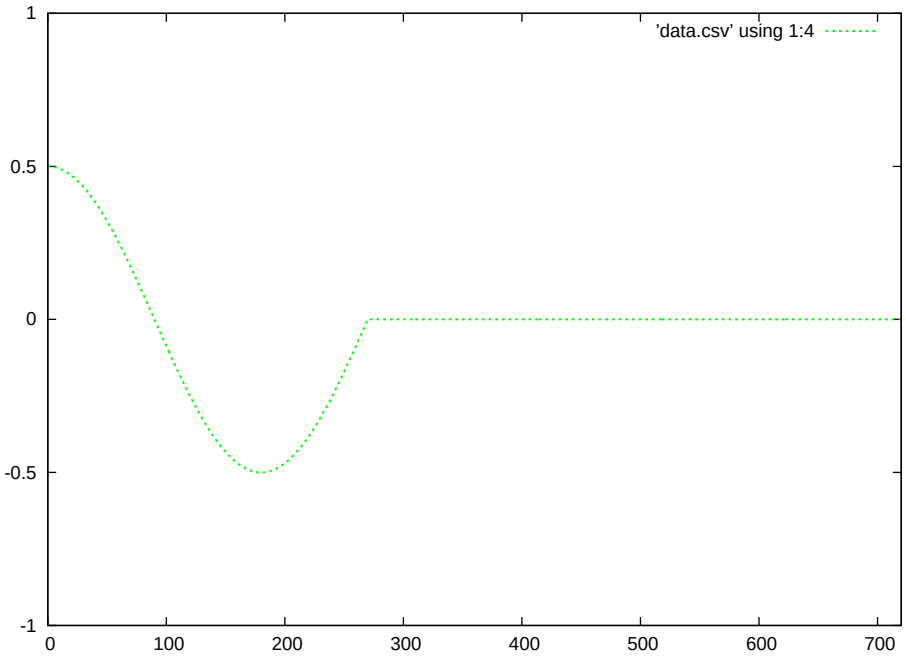

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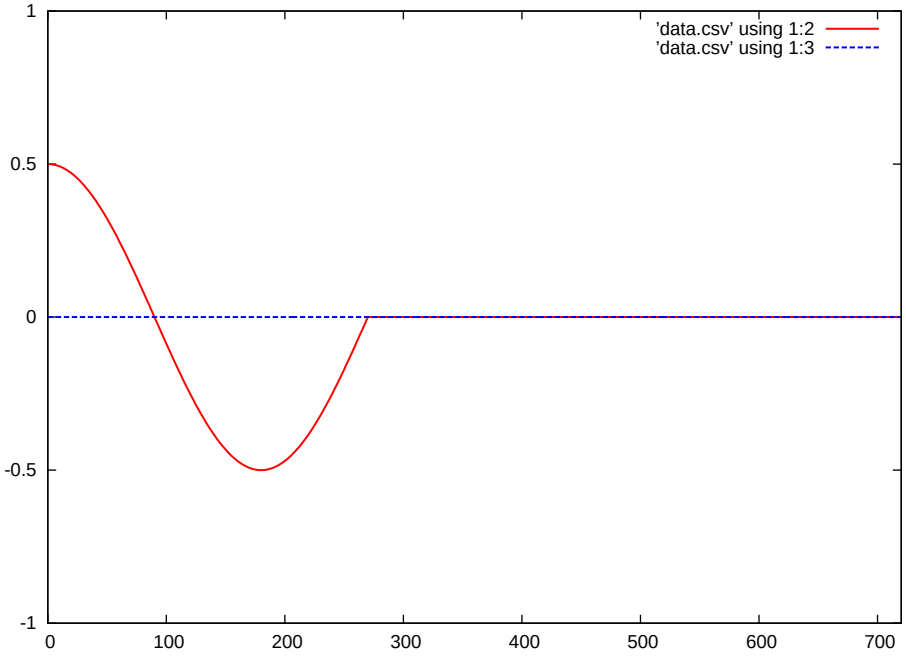

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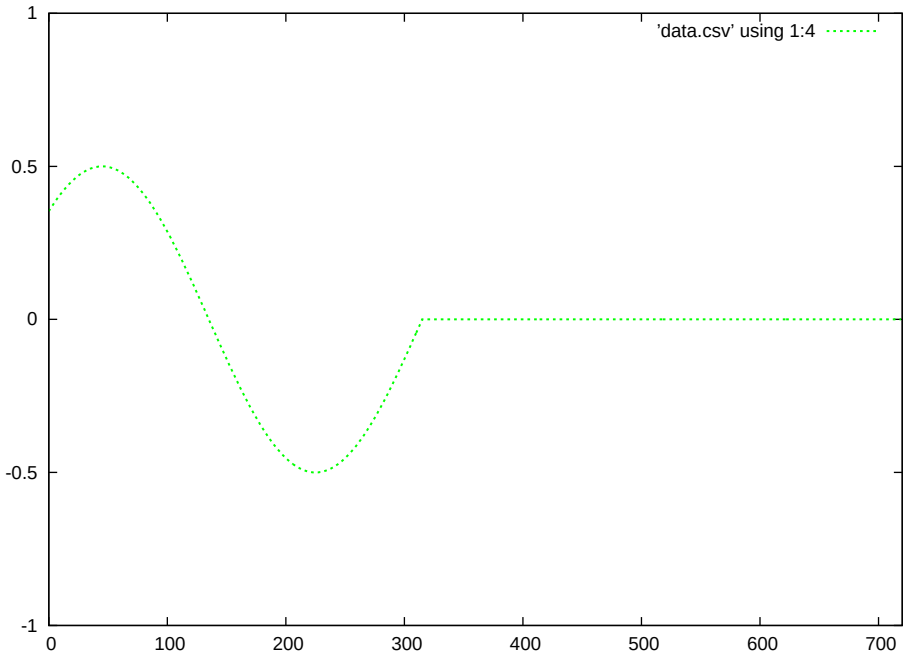

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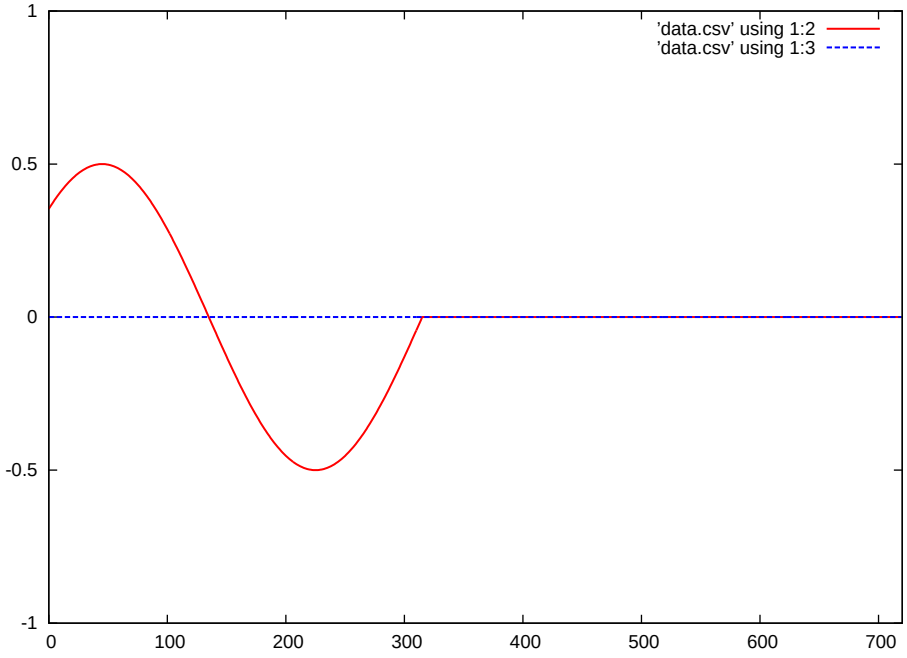

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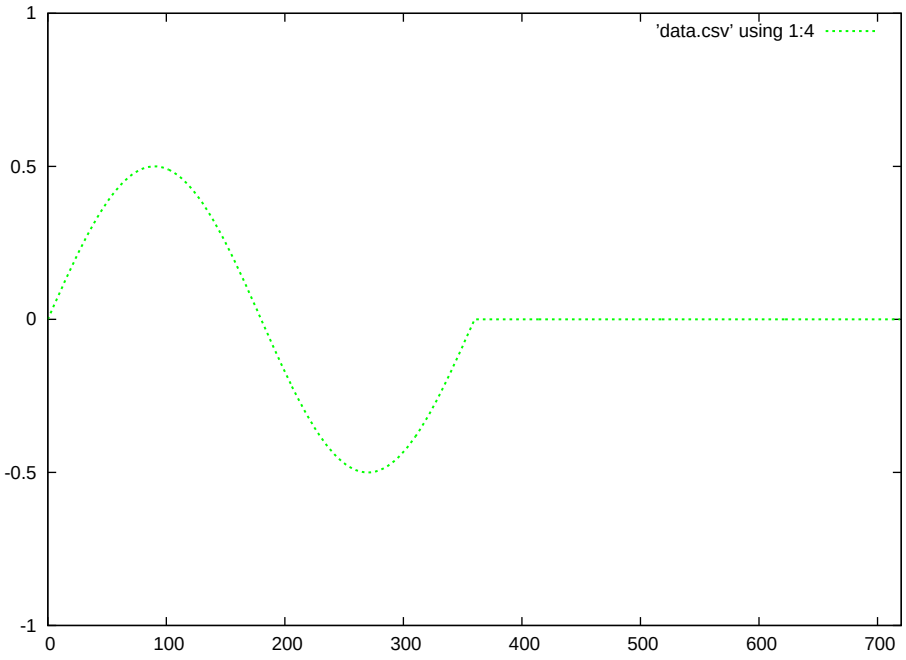

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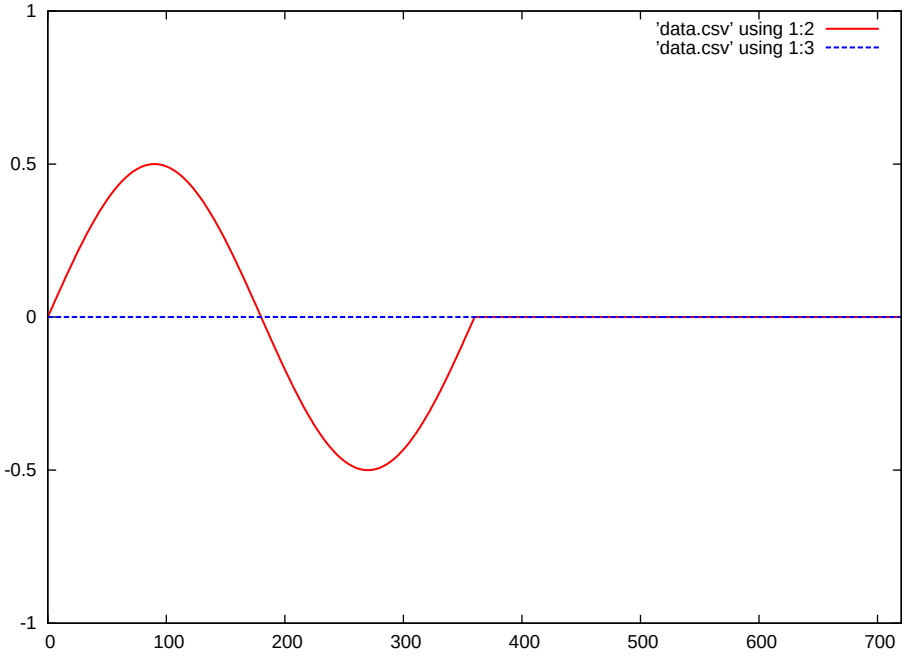

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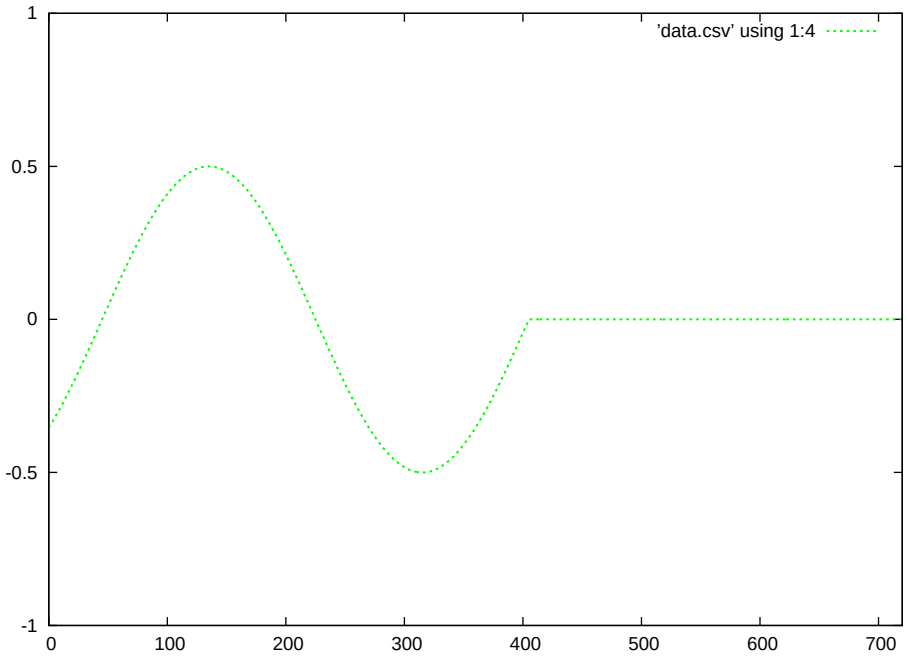

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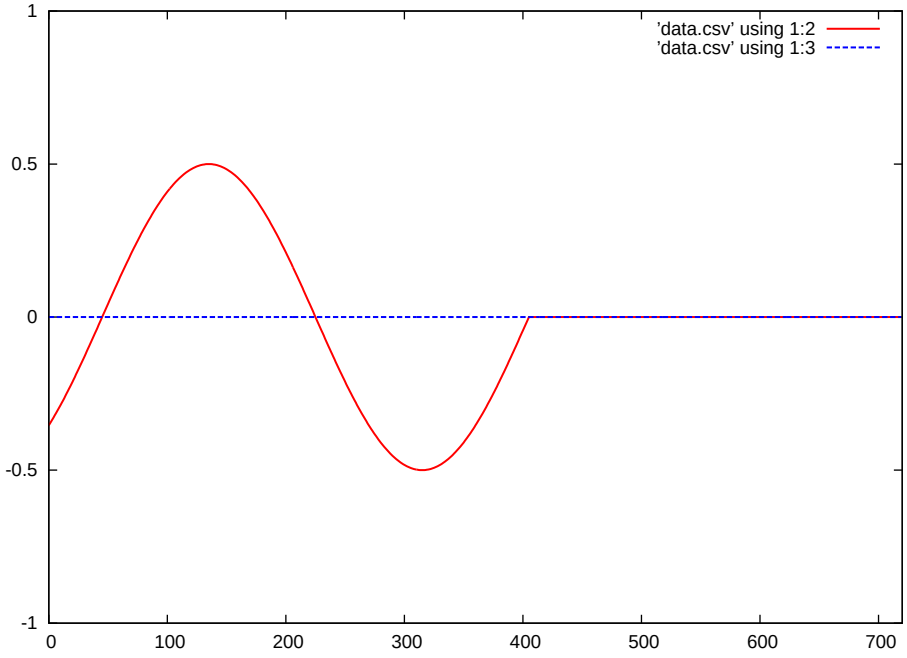

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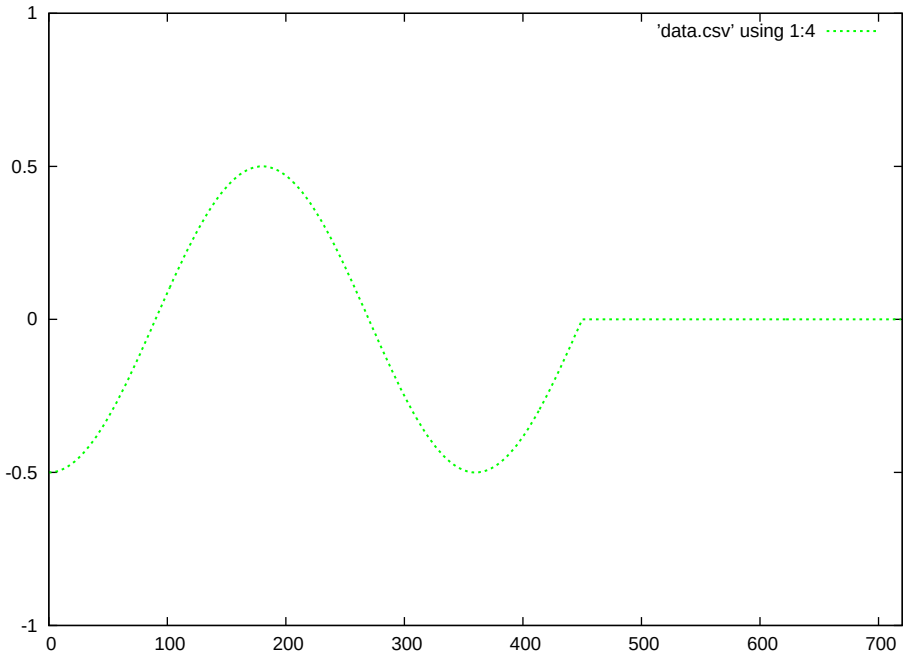

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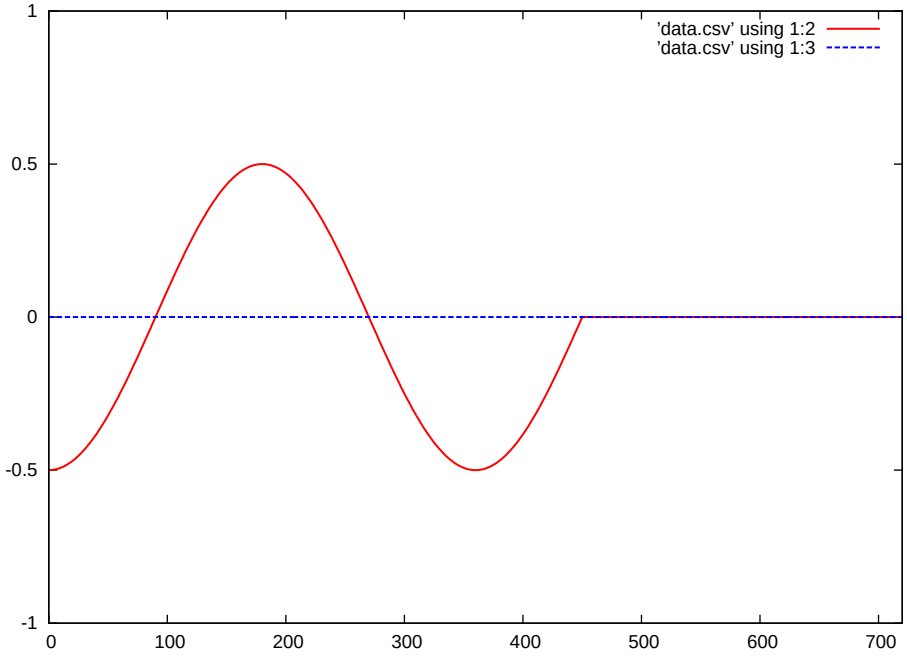

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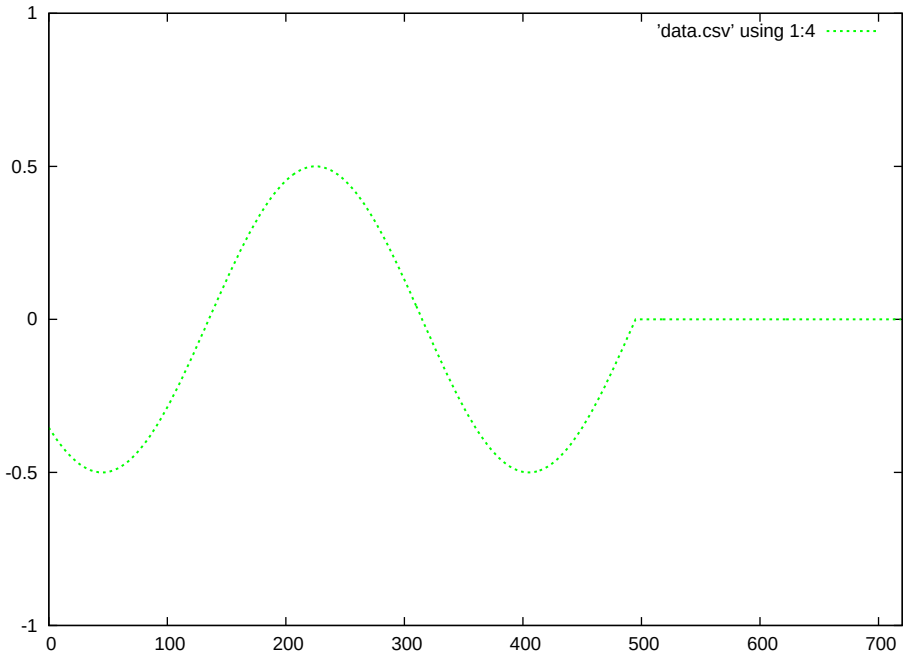

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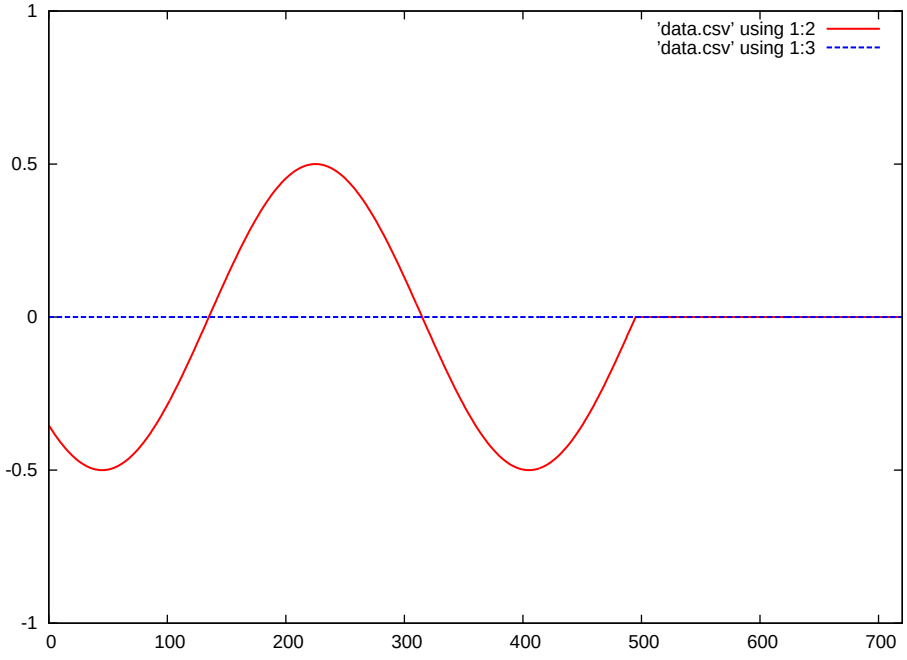

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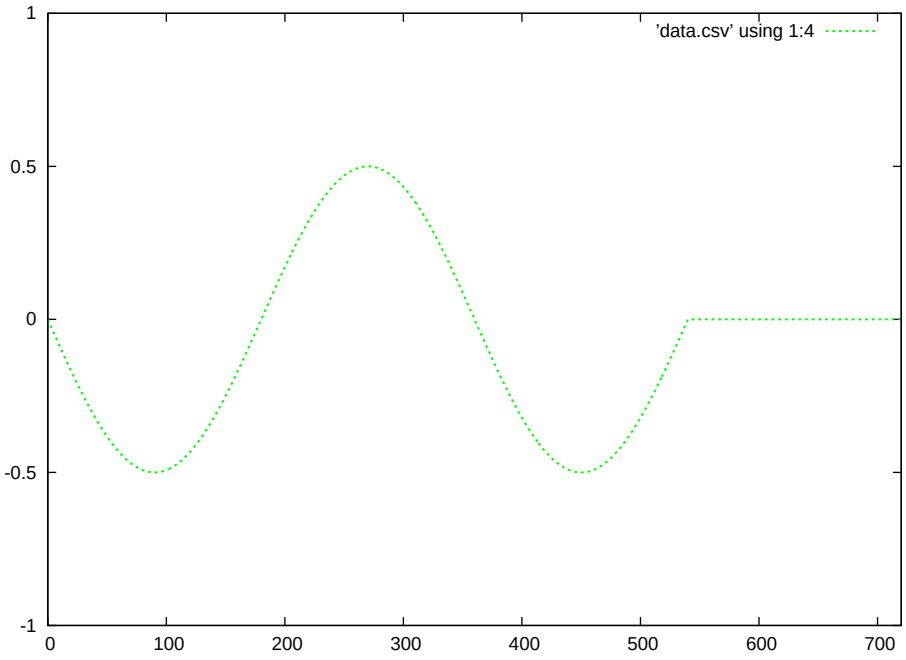

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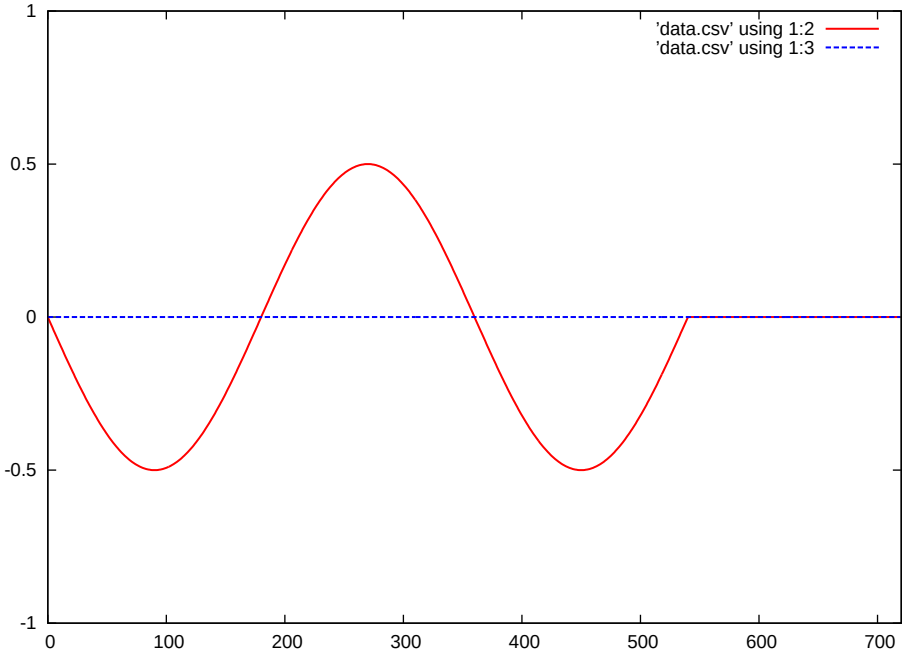

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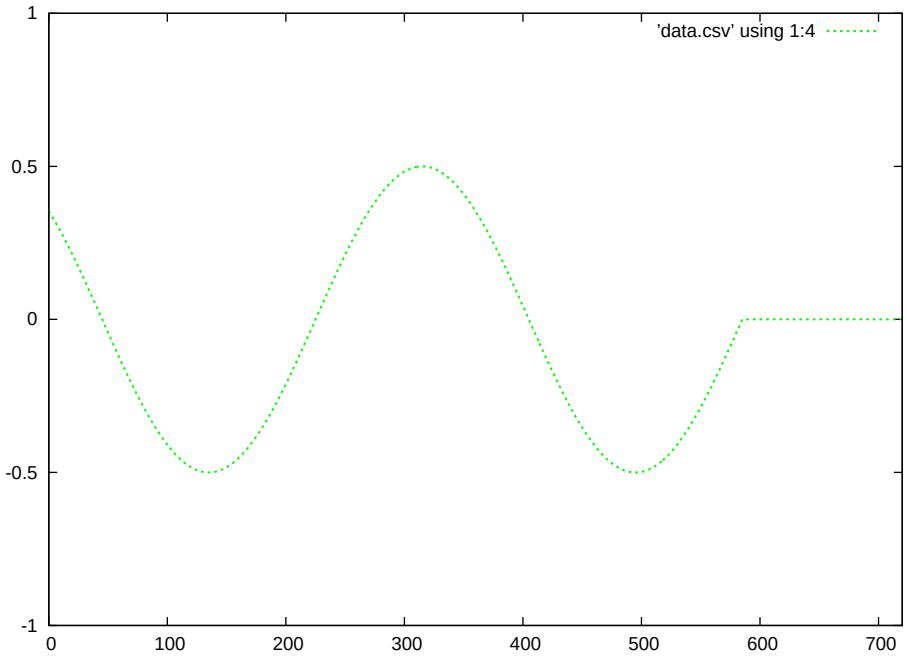

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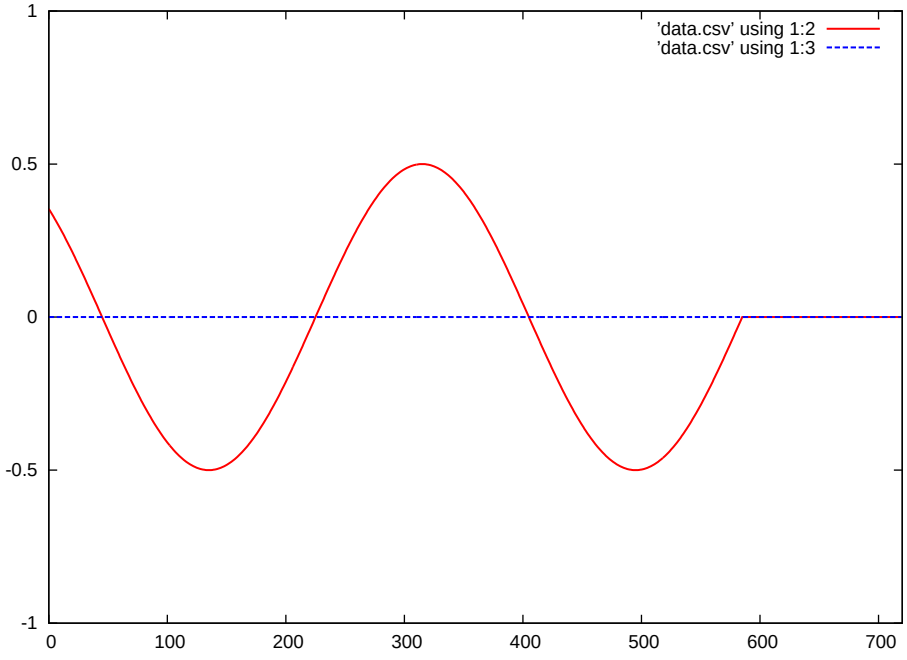

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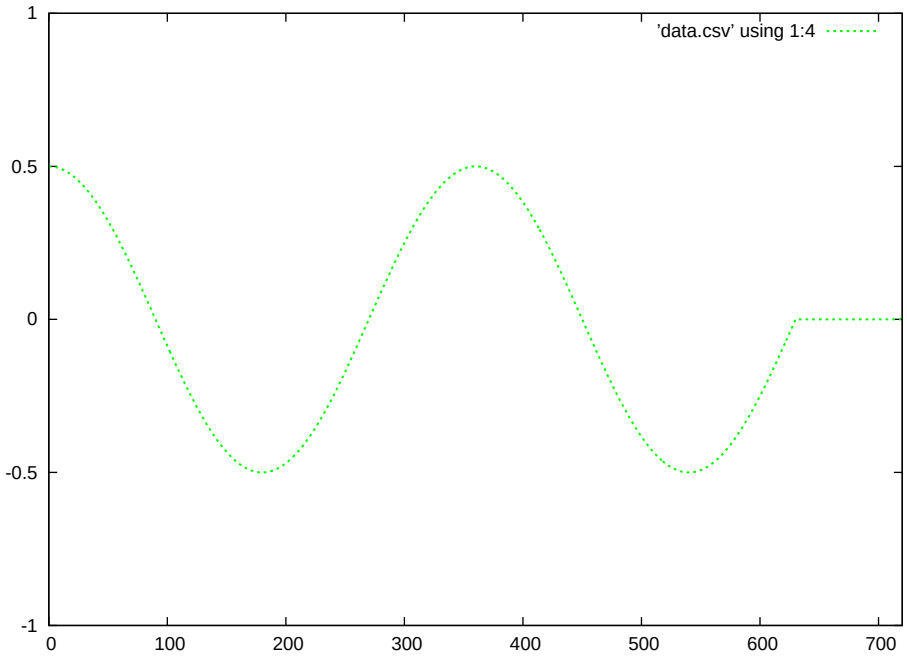

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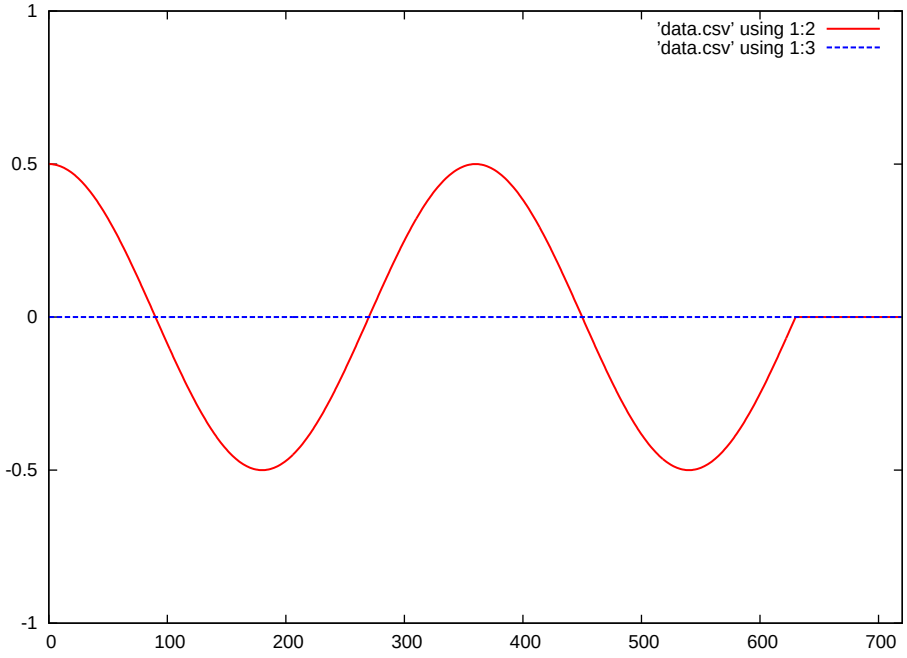

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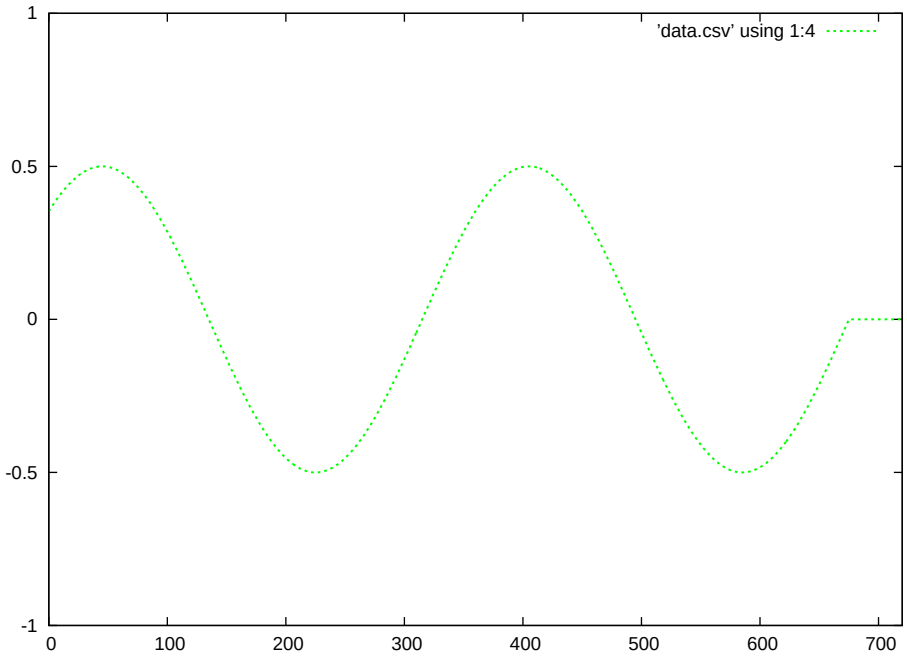

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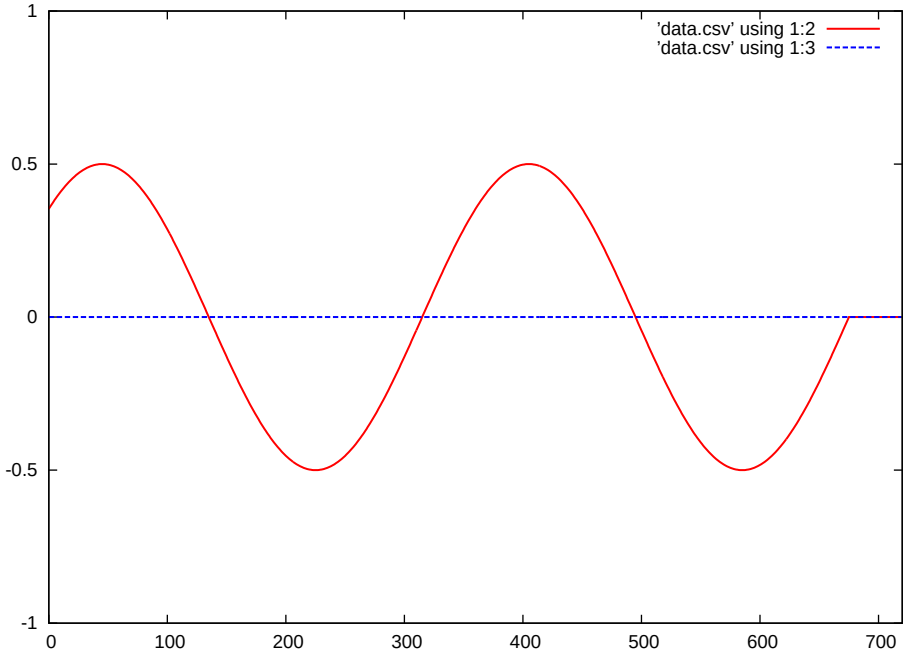

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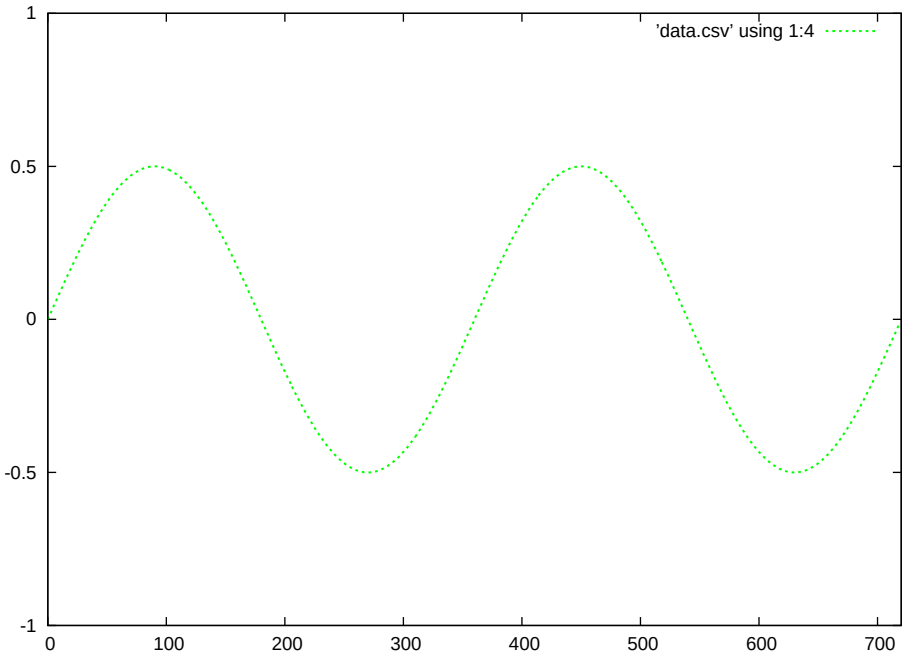

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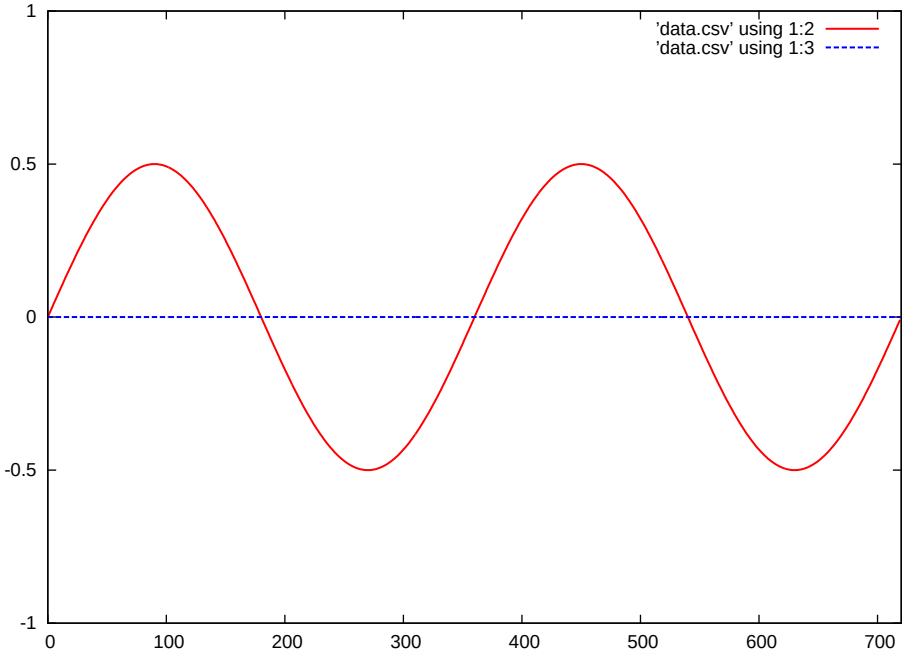

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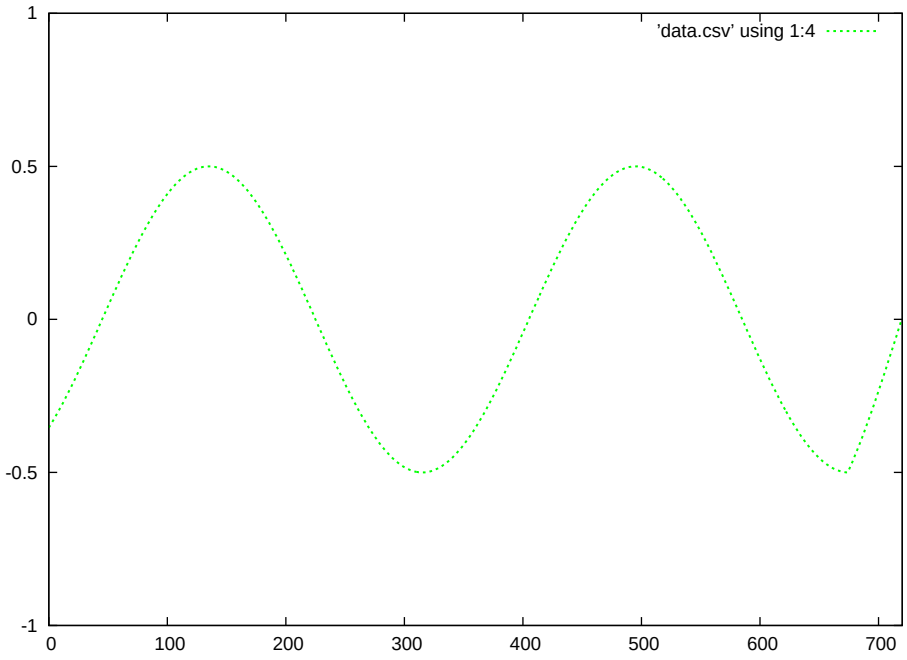

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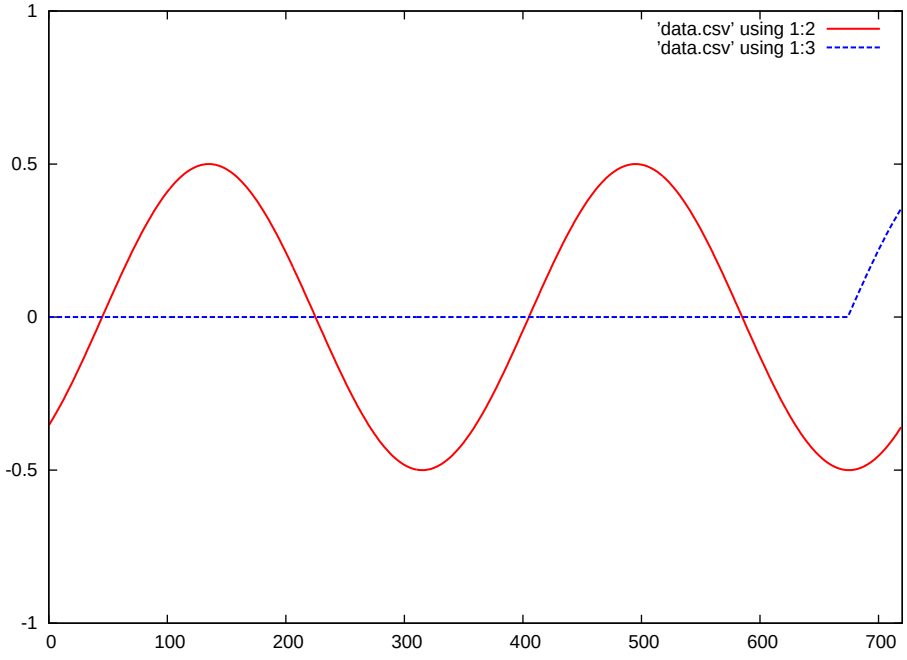

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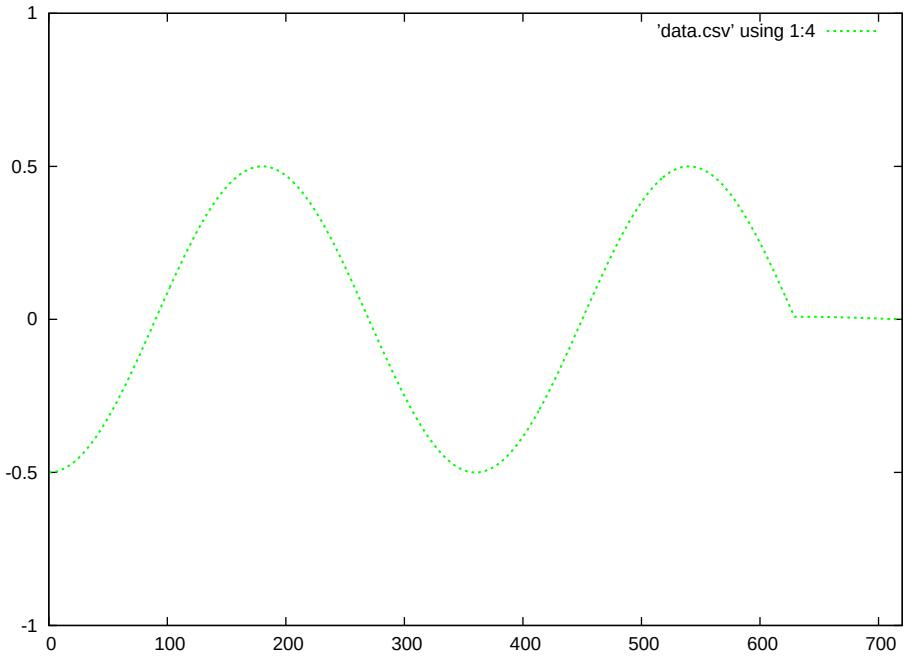

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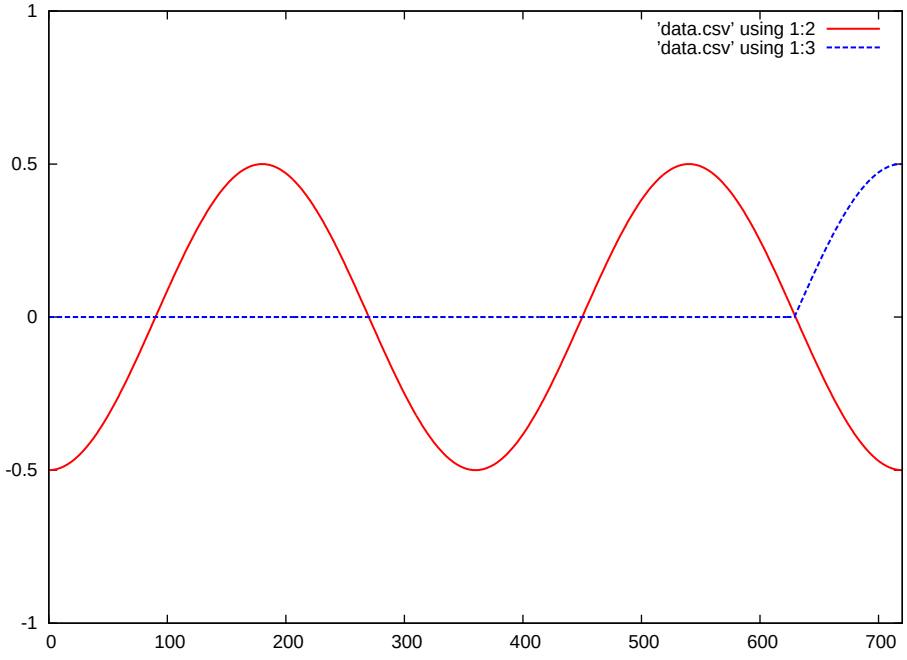

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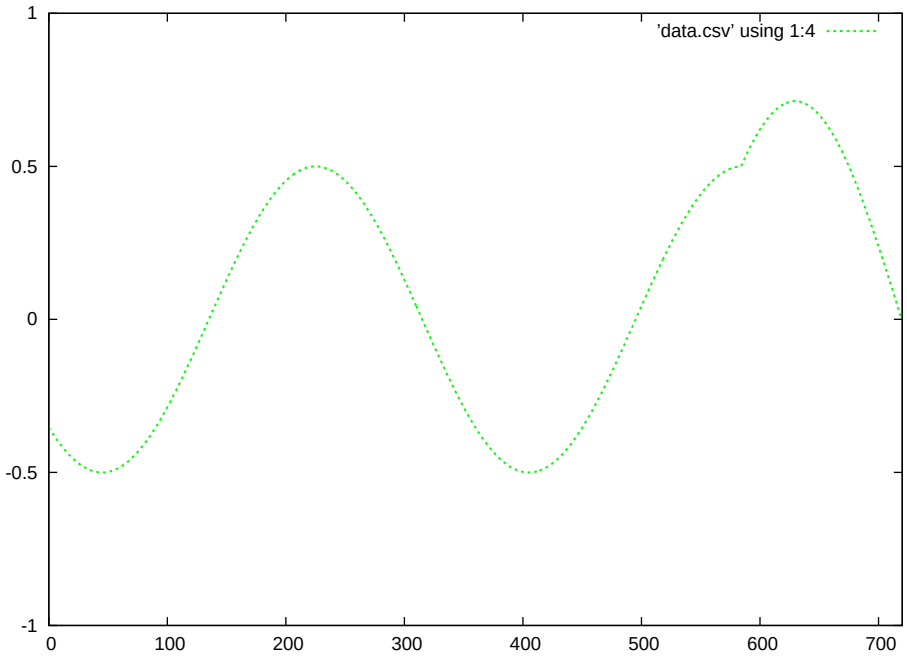

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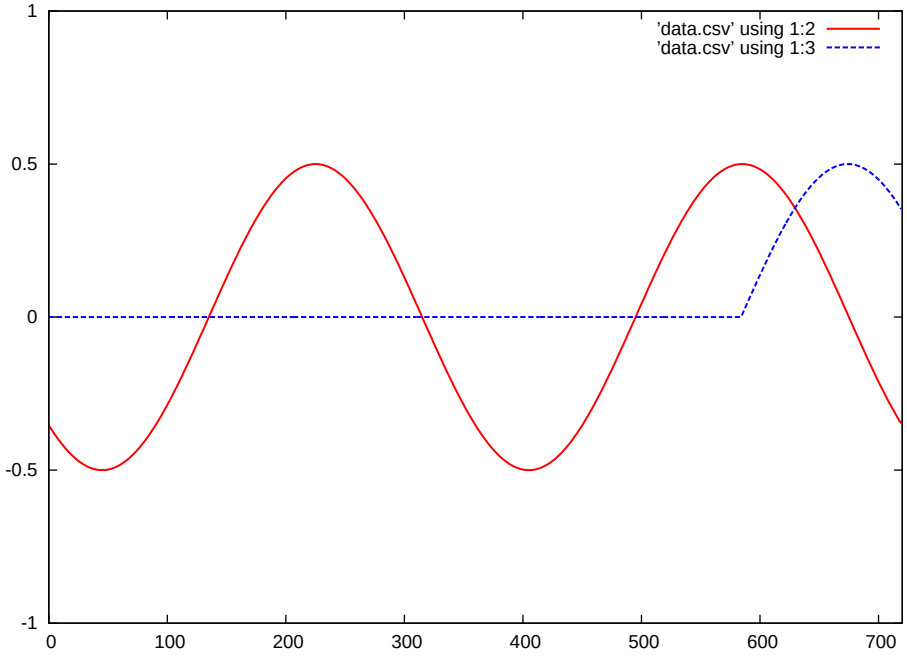

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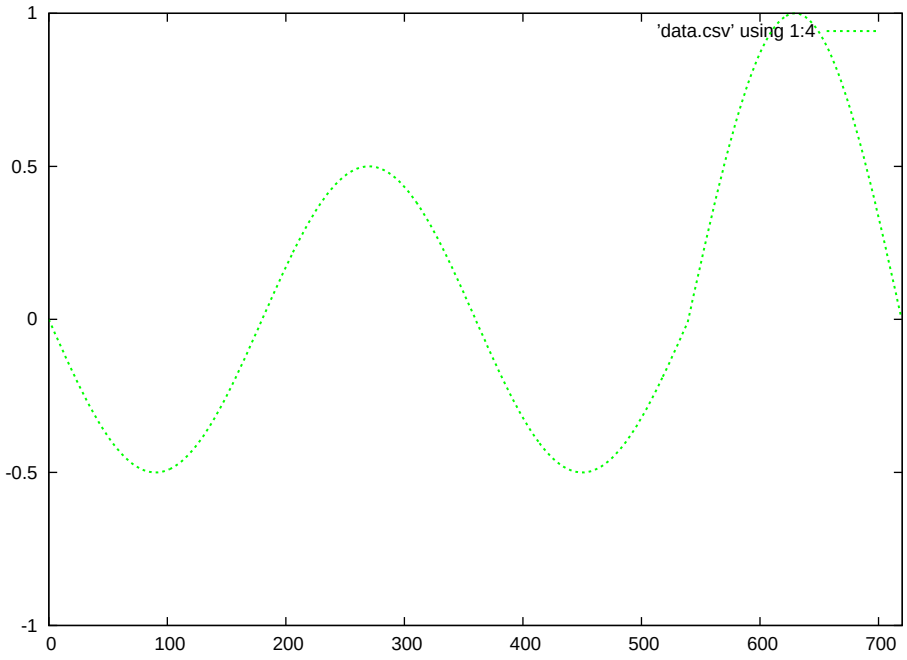

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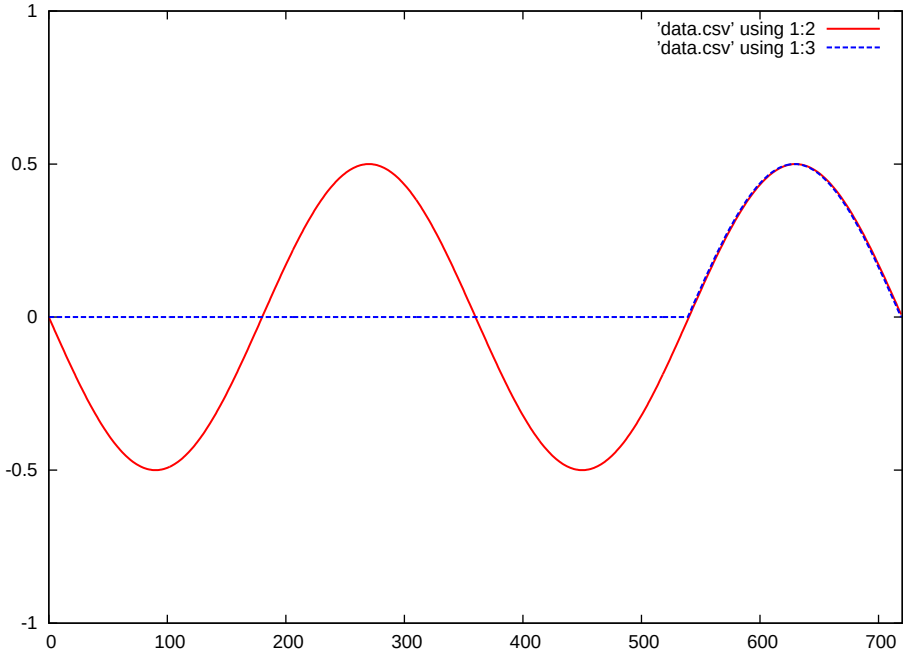

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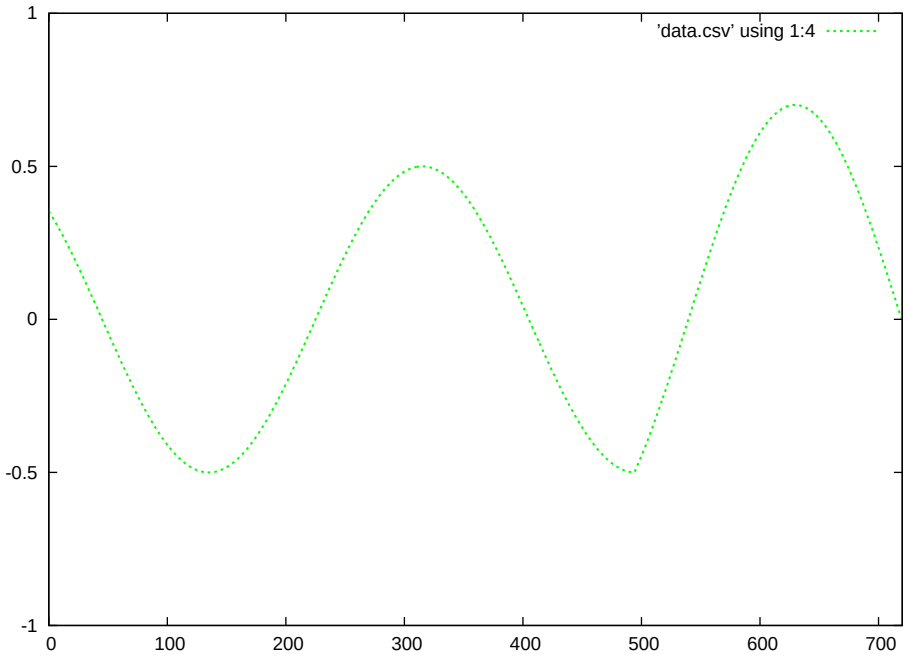

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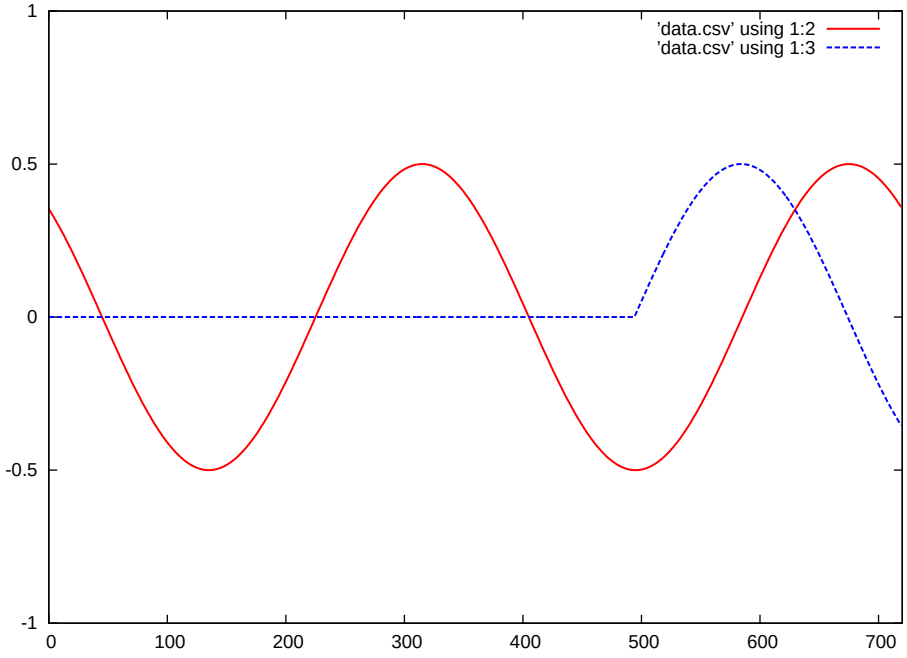

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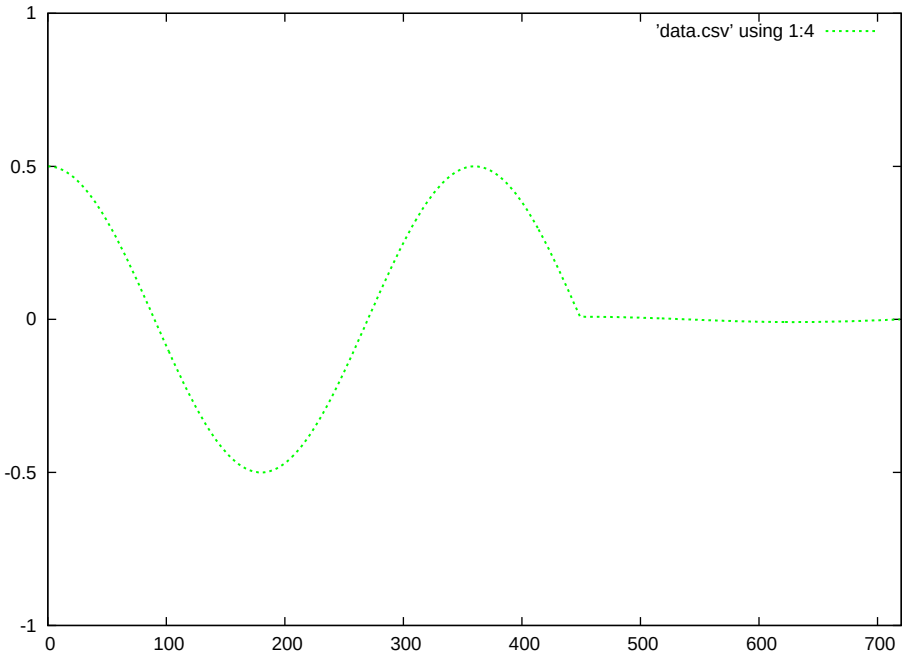

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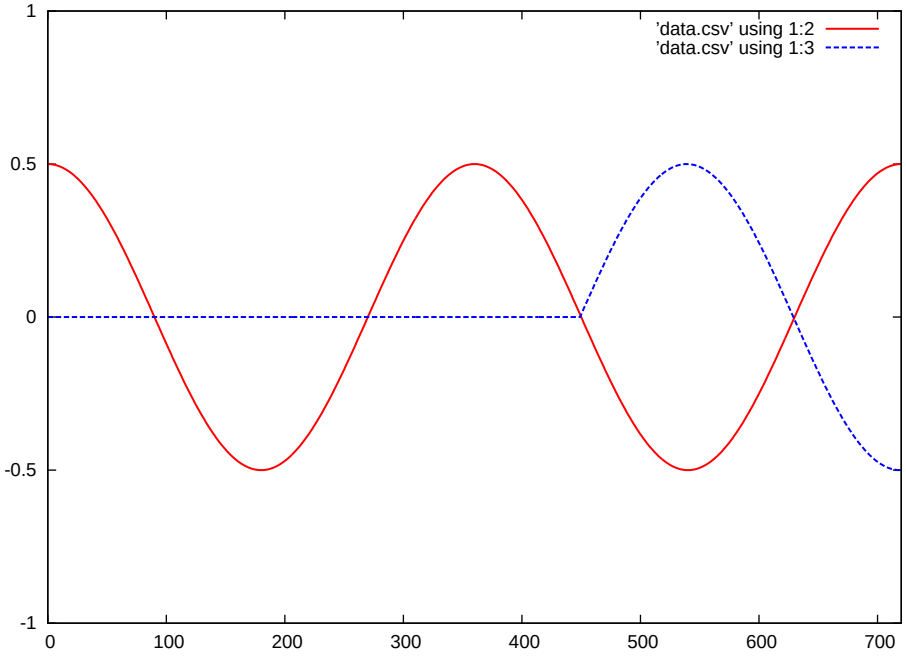

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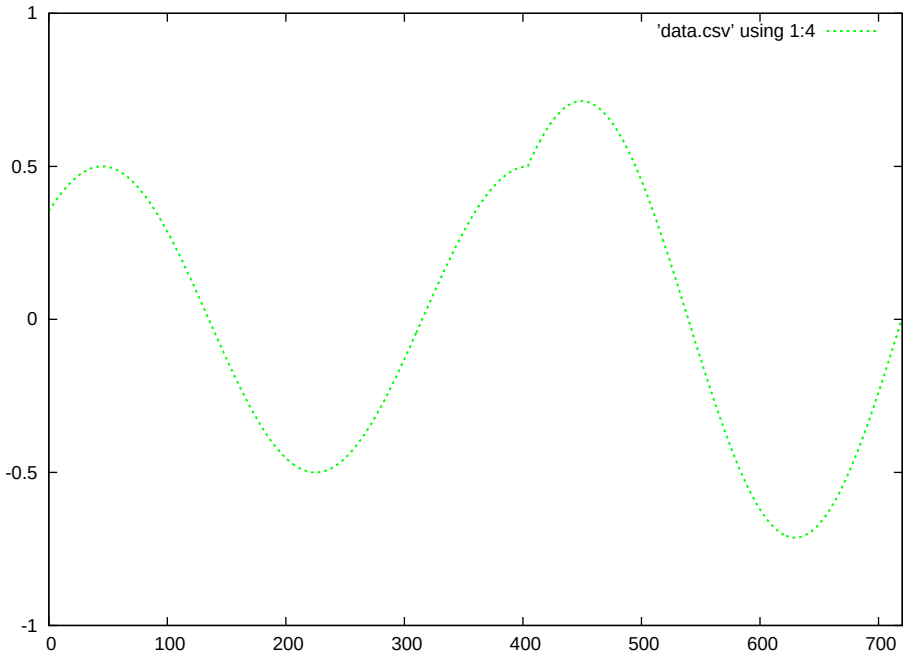

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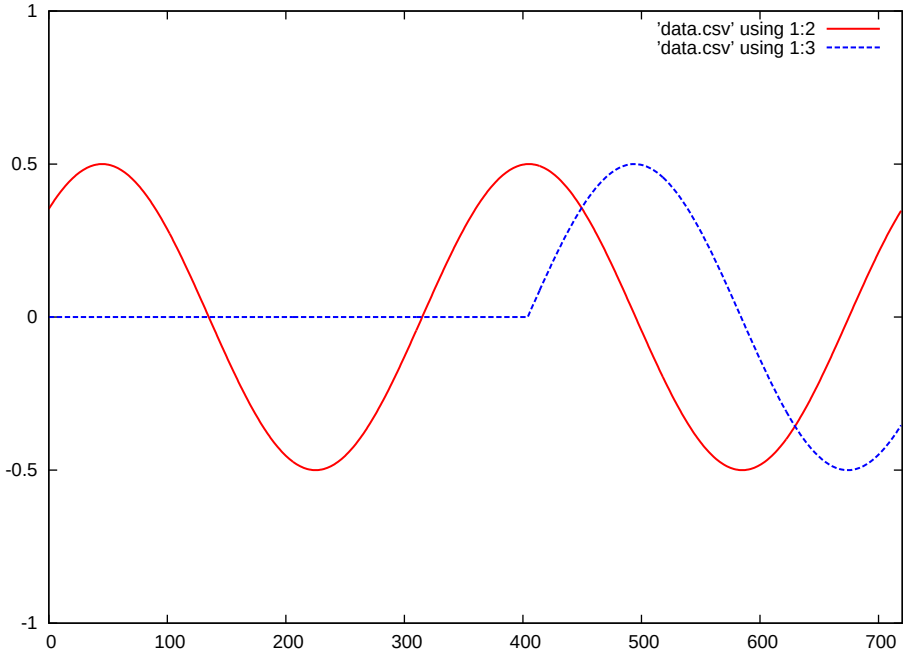

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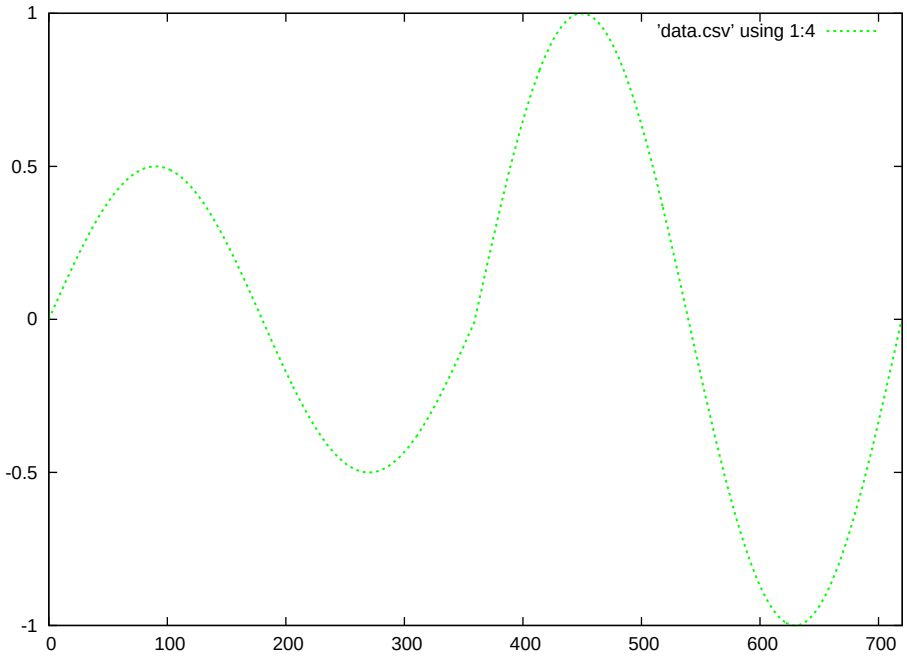

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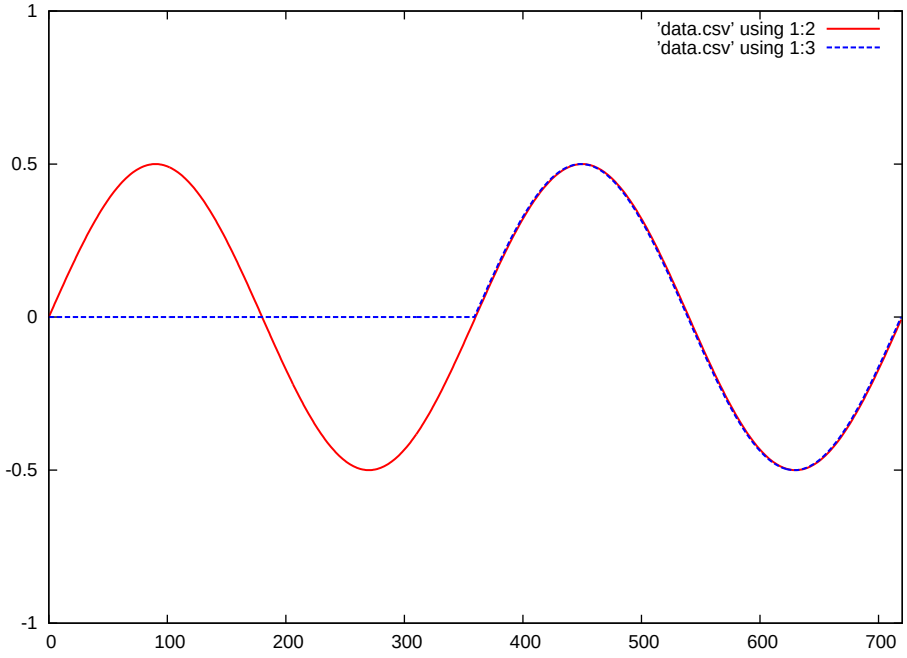

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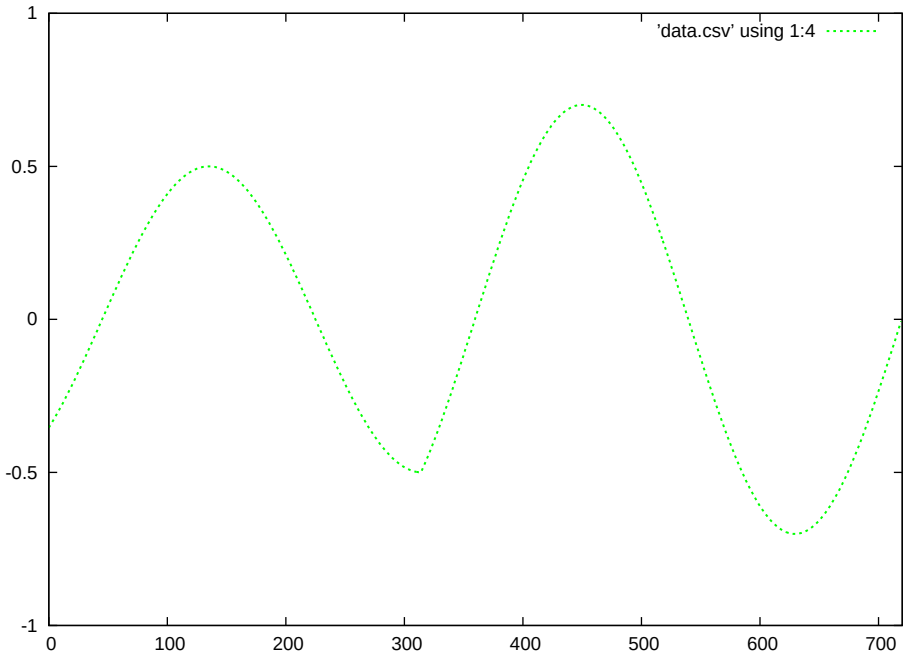

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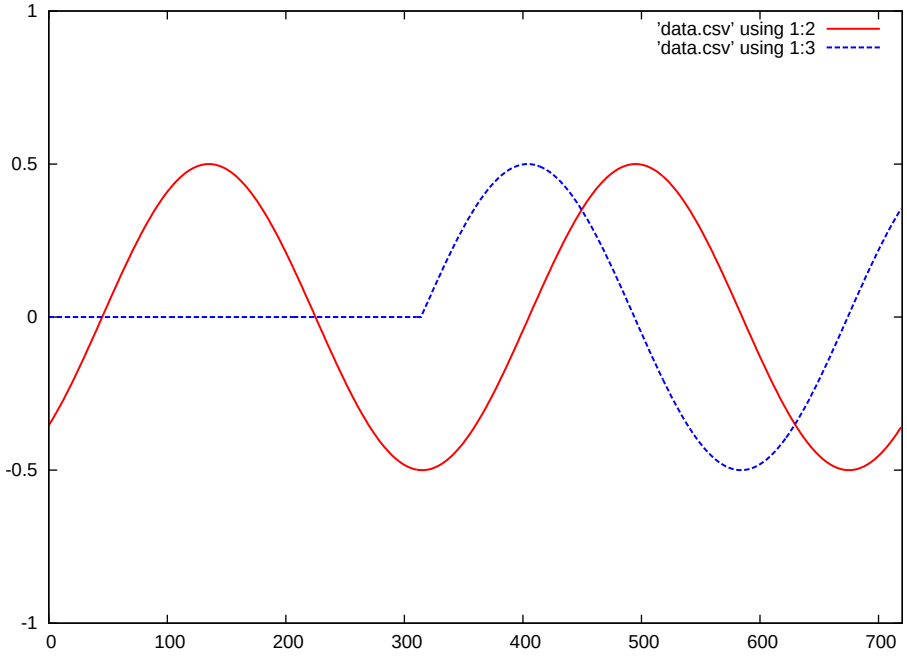

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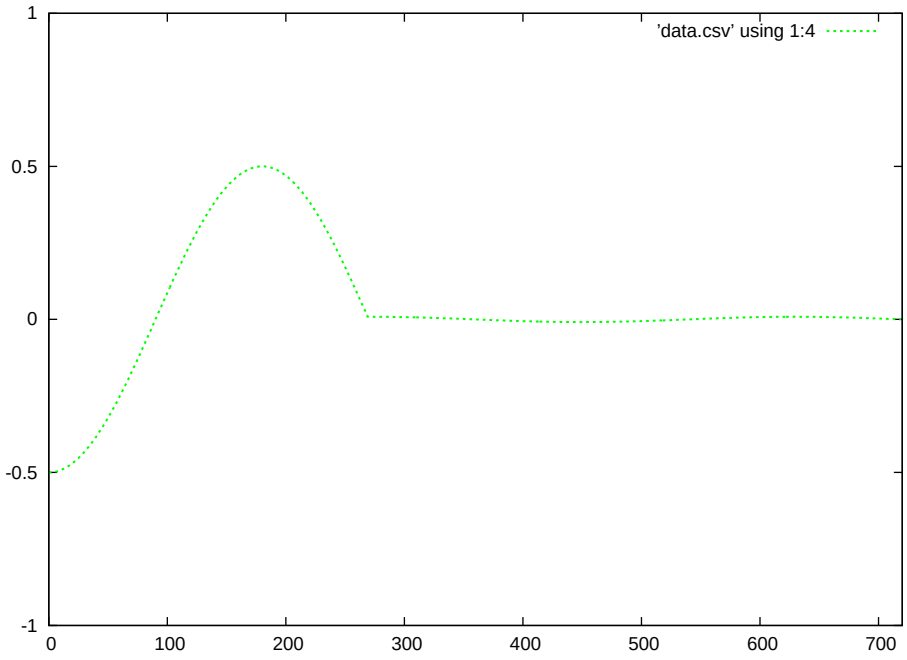

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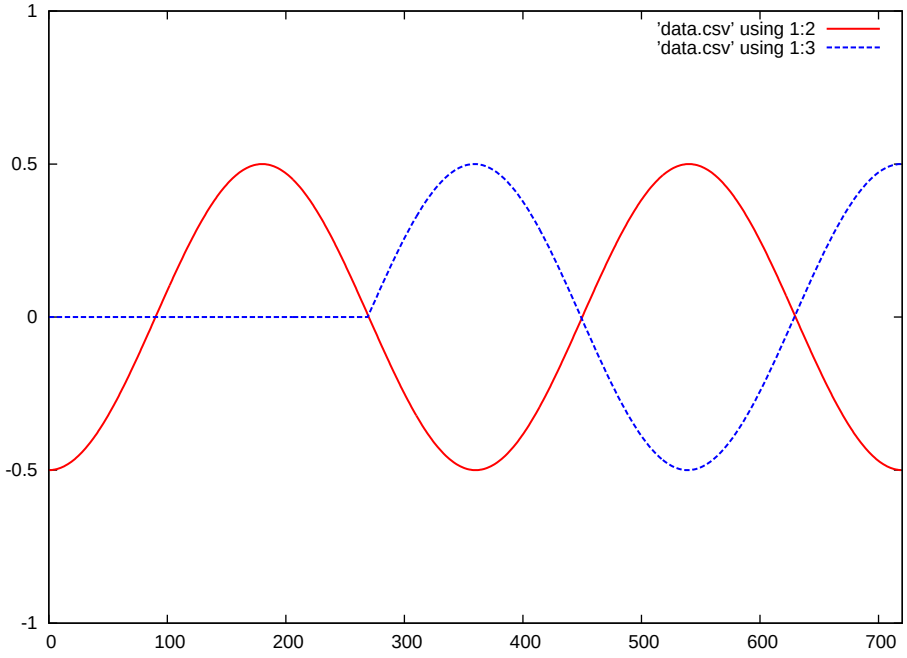

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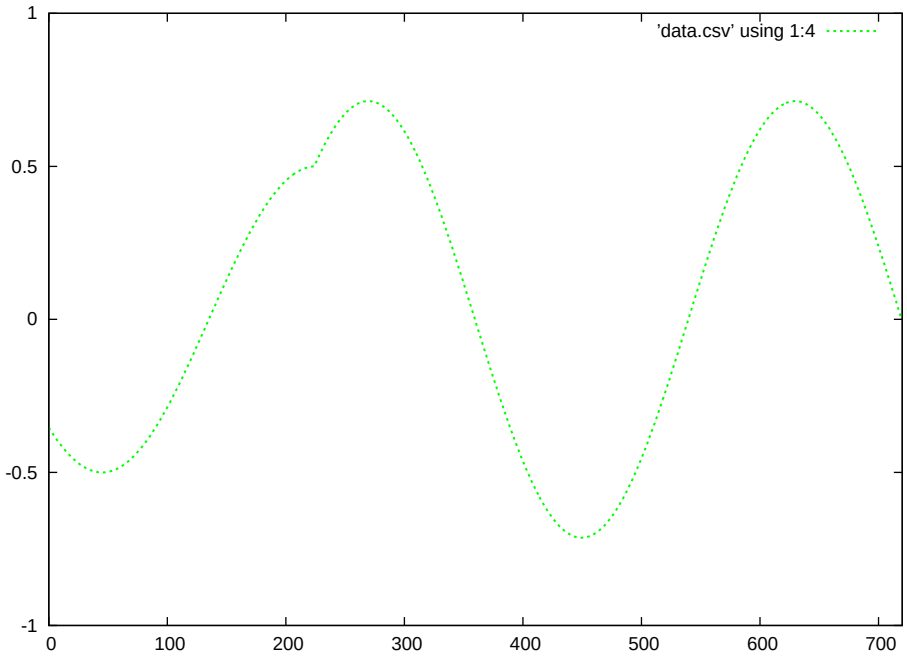

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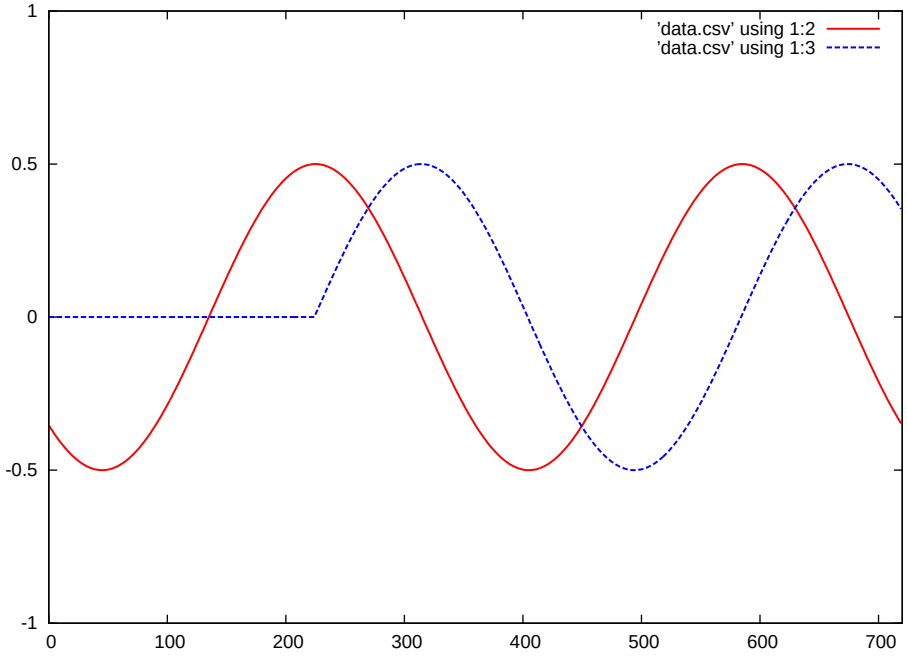

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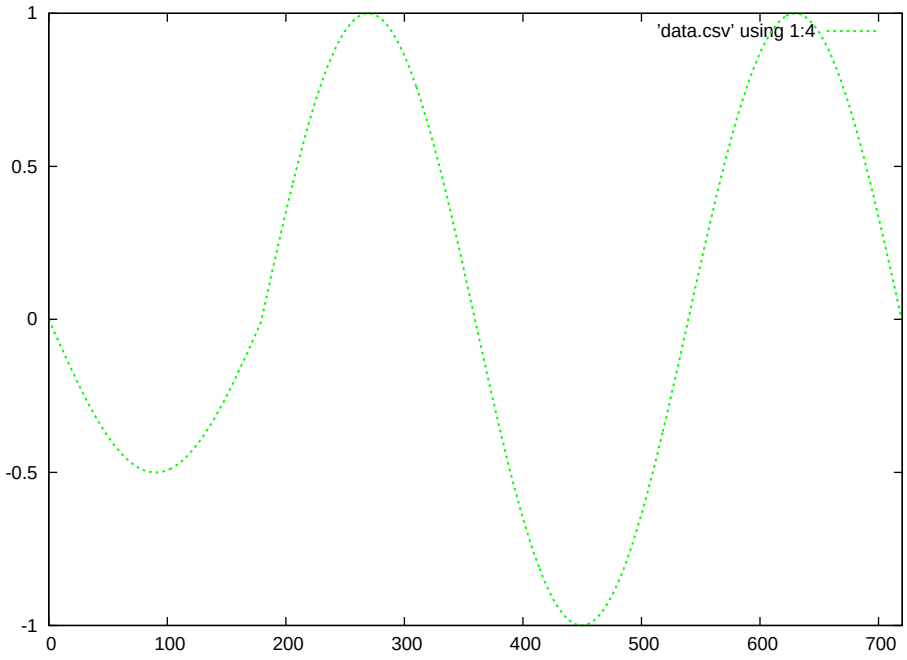

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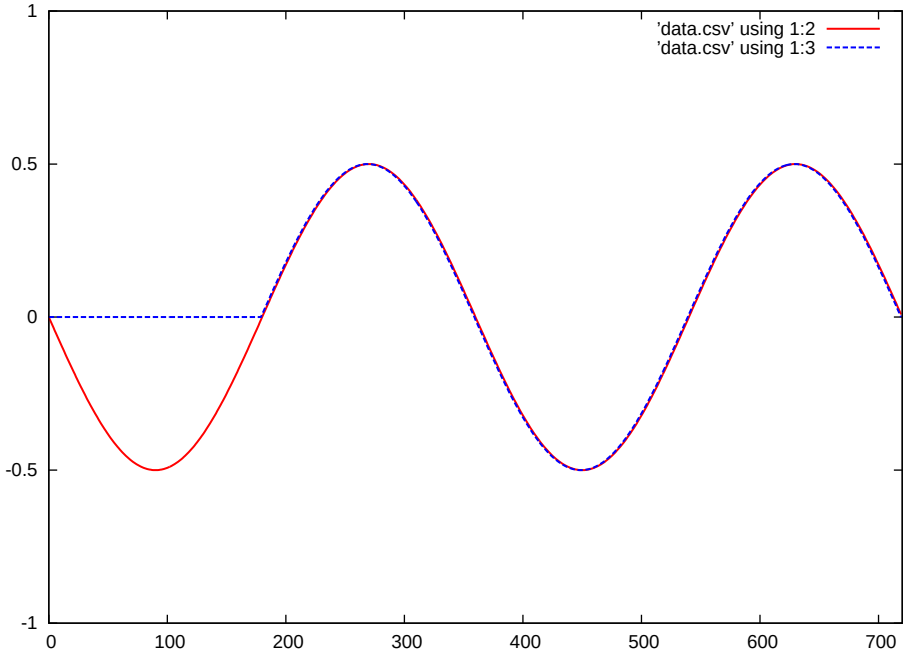

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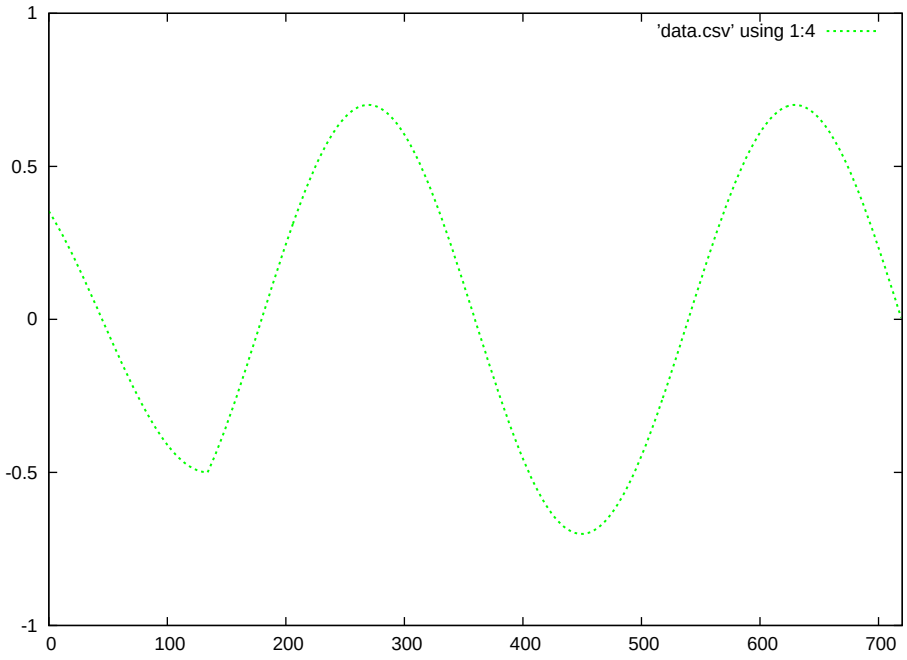

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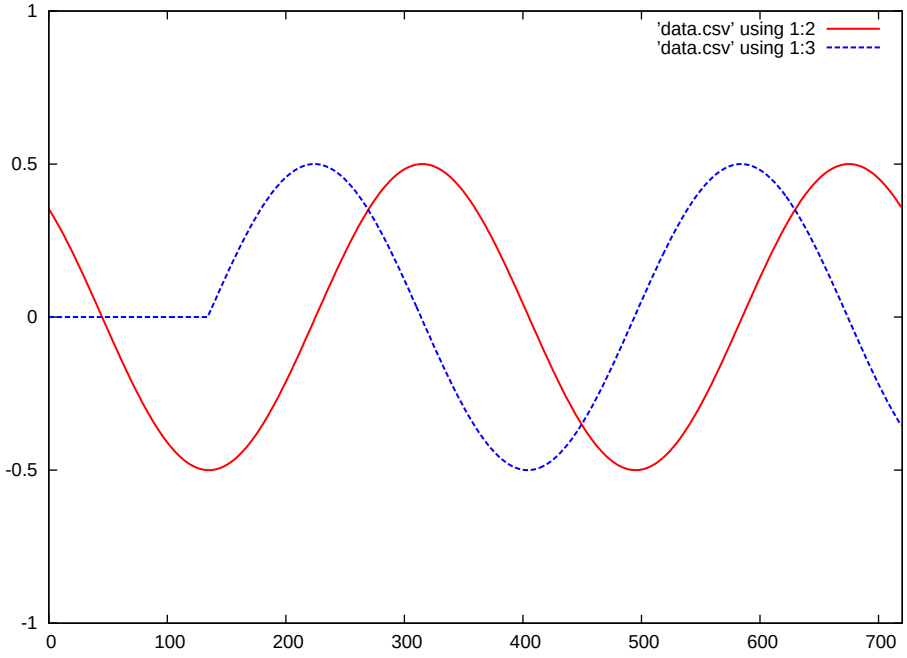

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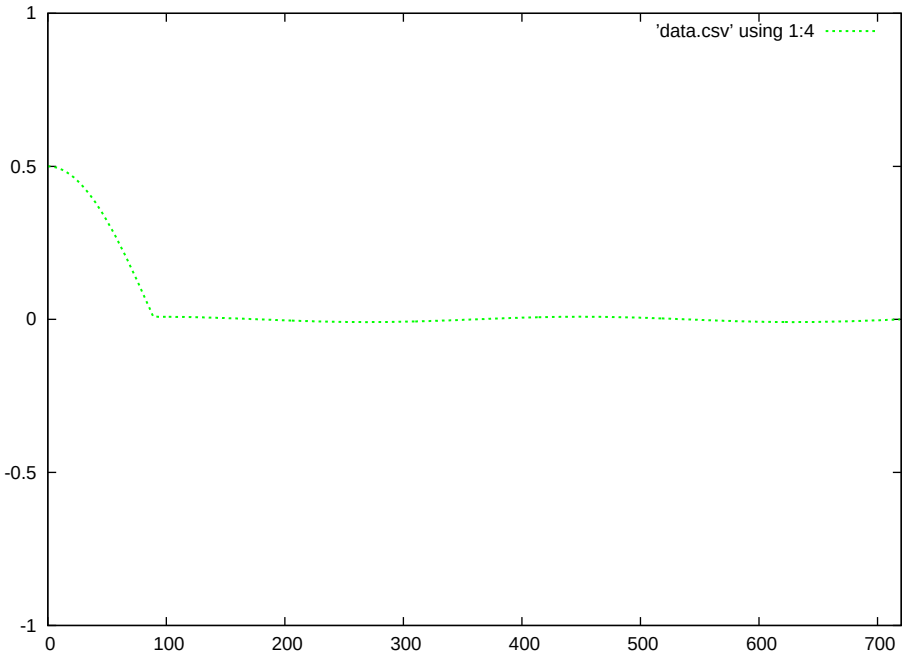

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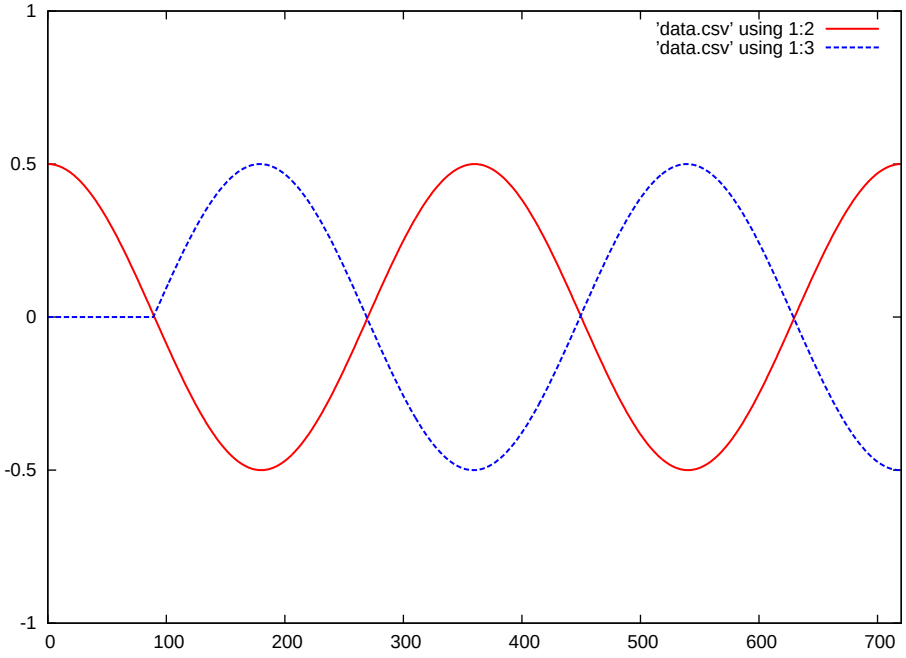
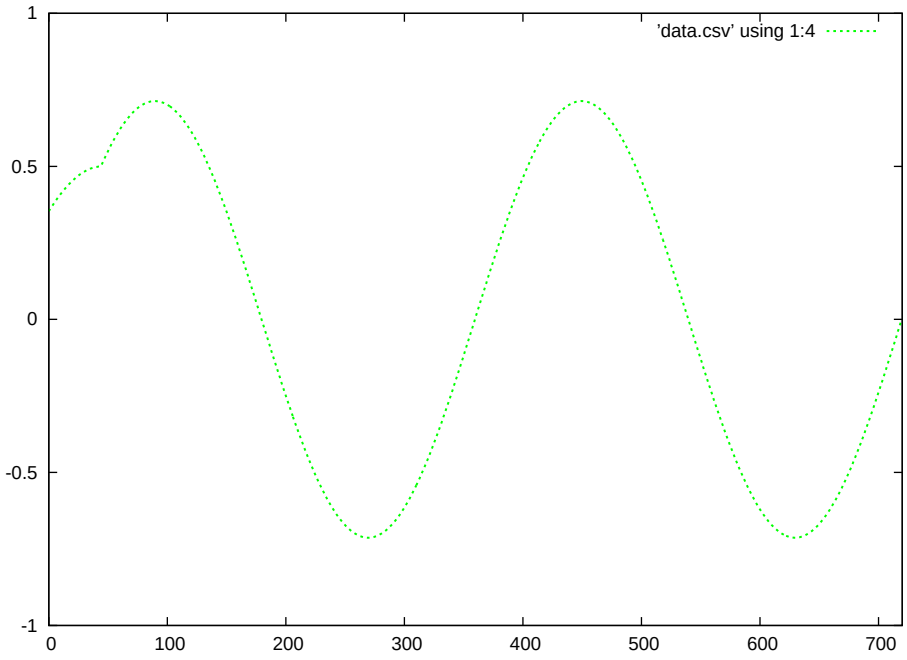
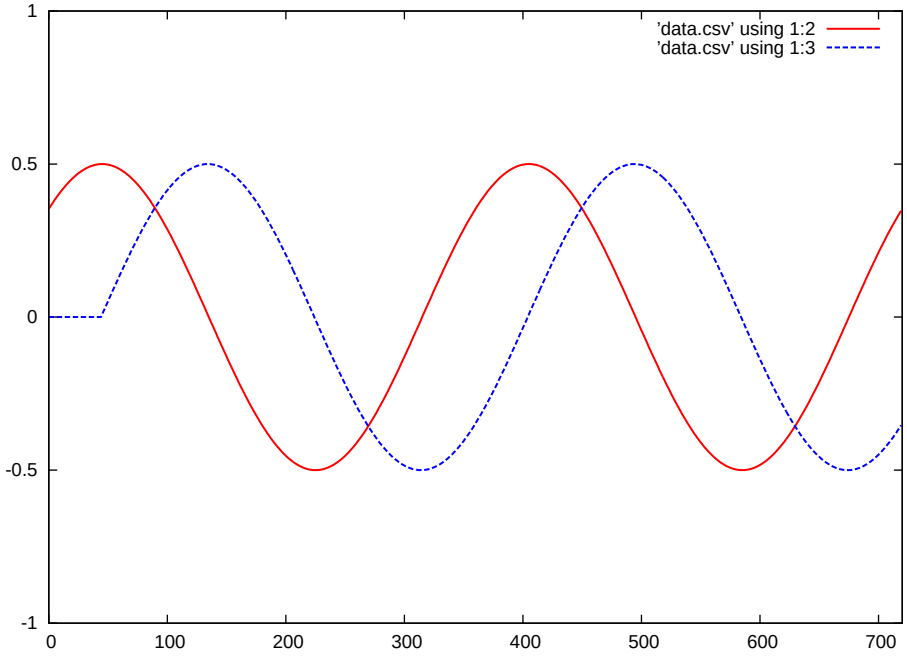


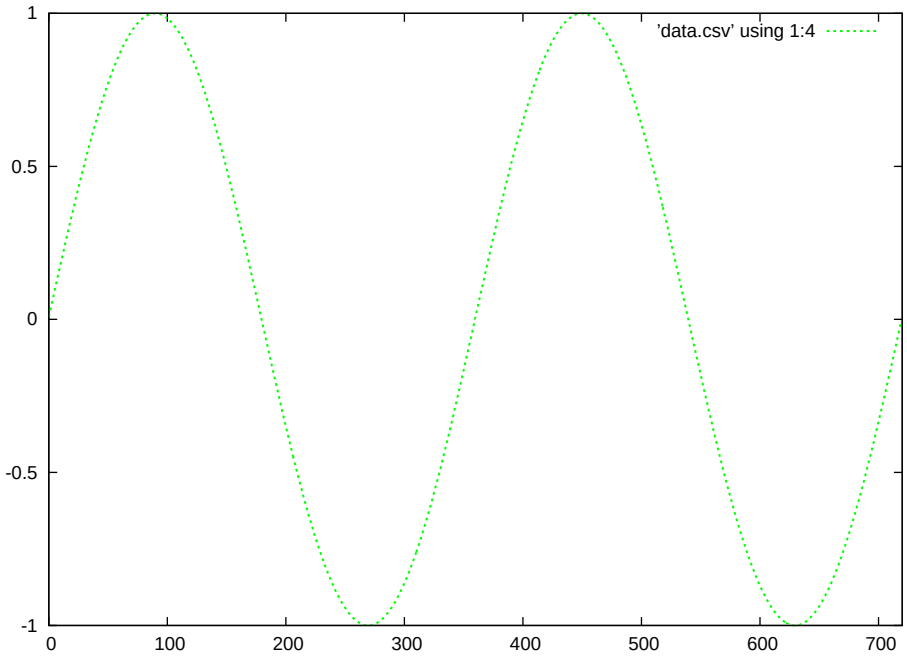
Green = superposition of the forward and reflected waves



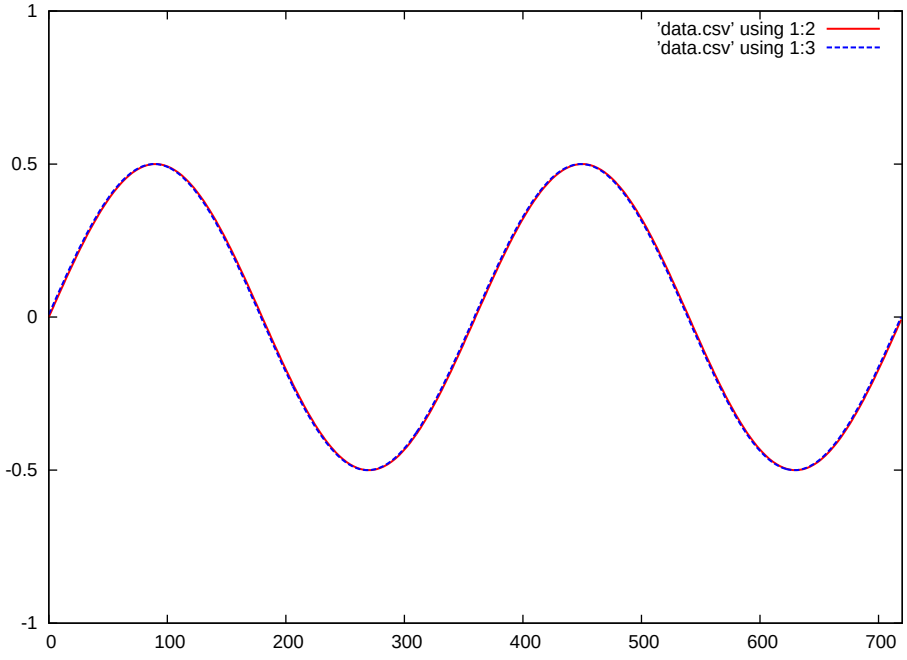
Red = forward wave Blue = reflected wave



Green = superposition of the forward and reflected waves

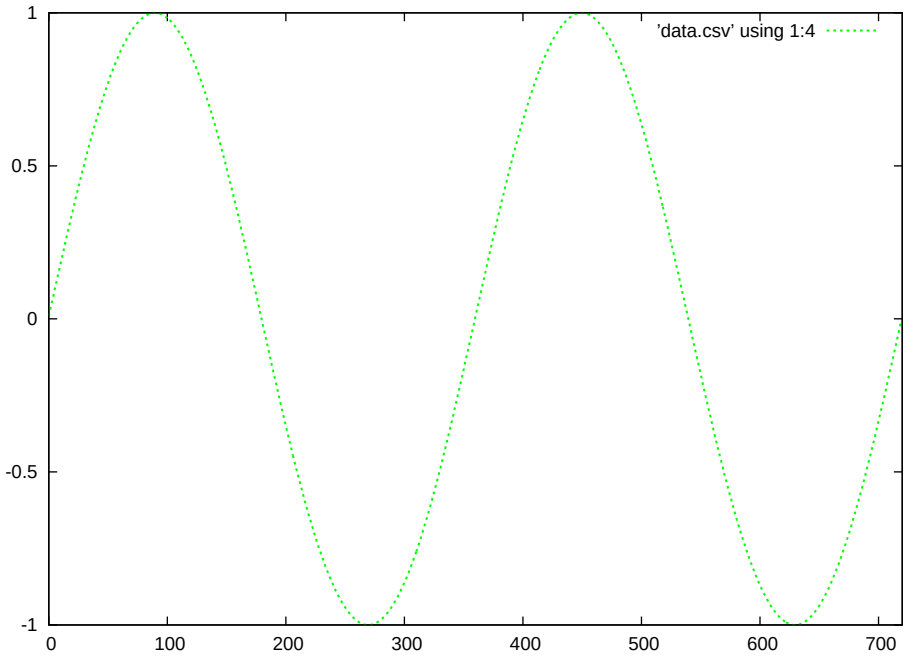


Red = forward wave Blue = reflected wave

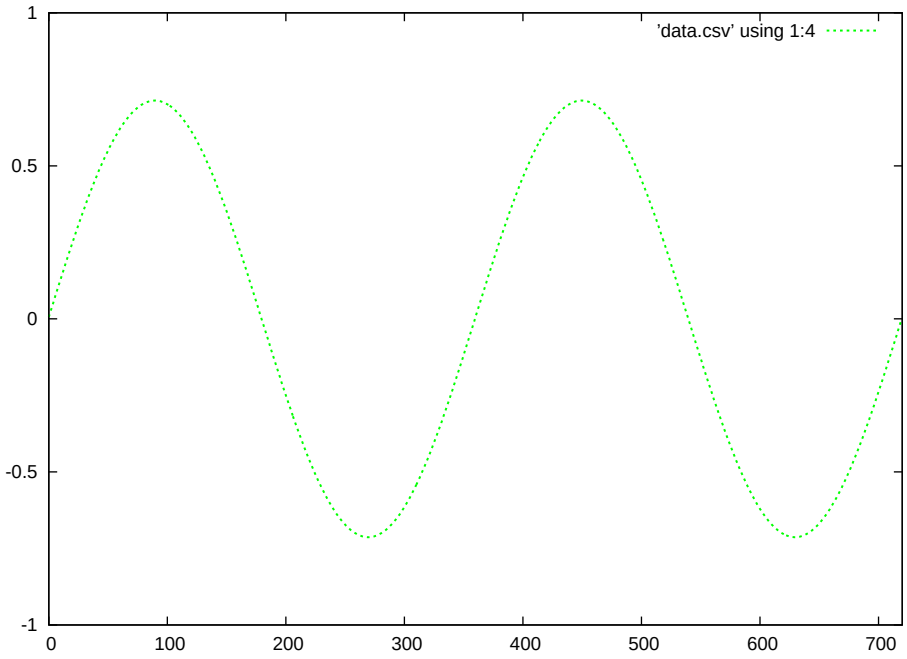


After the reflected wave has traveled all the way back to the source (left-hand end of the transmission line), the superposition of those two continuous waves results in a standing wave.

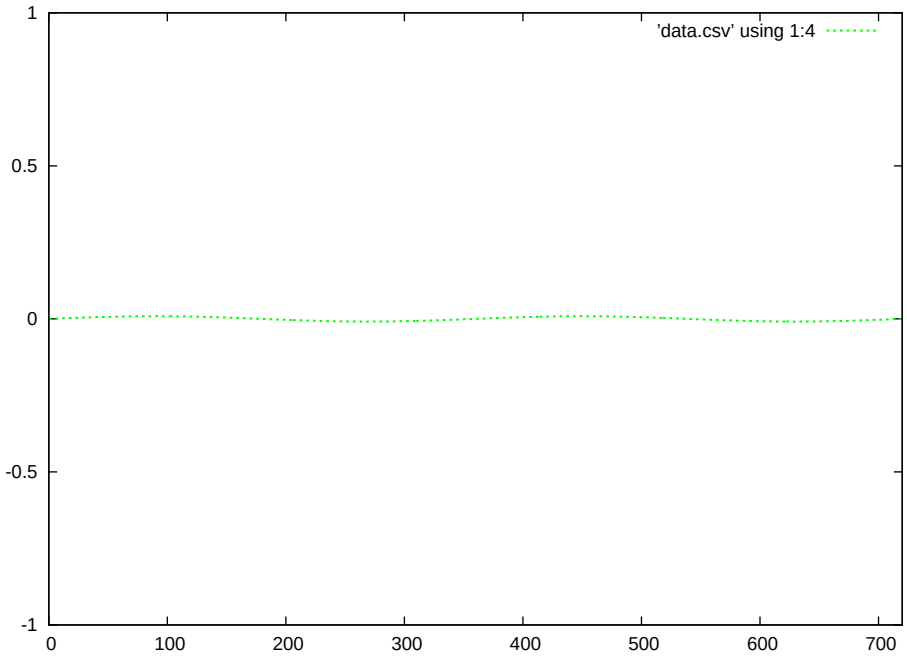
Green = standing wave



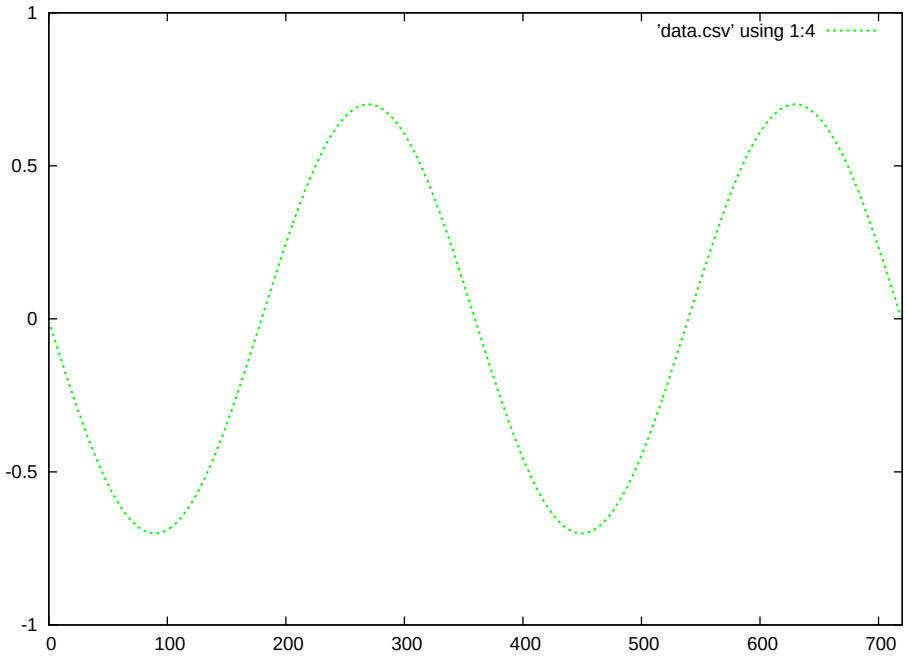
Green = standing wave



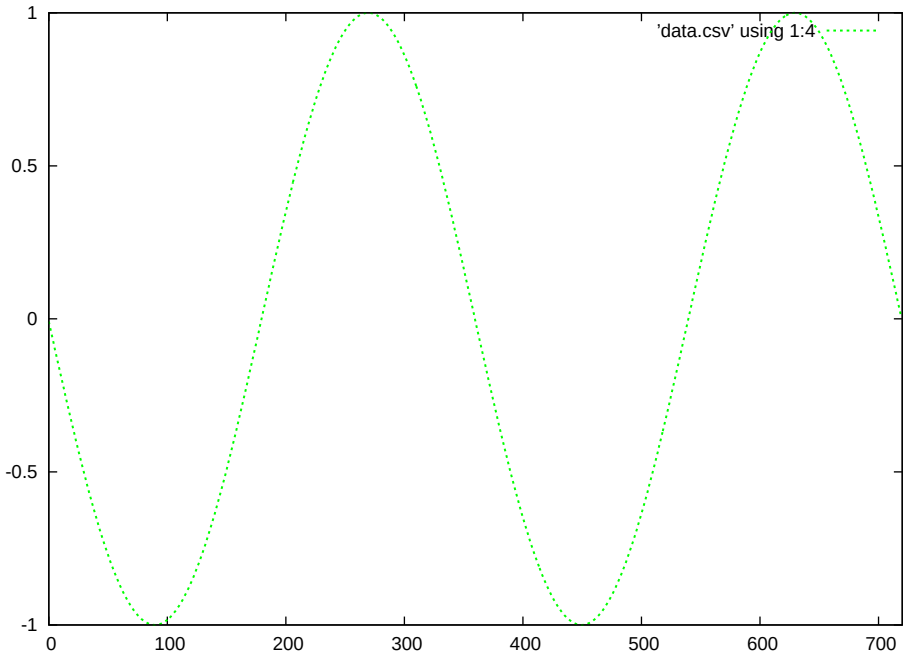
Green = standing wave



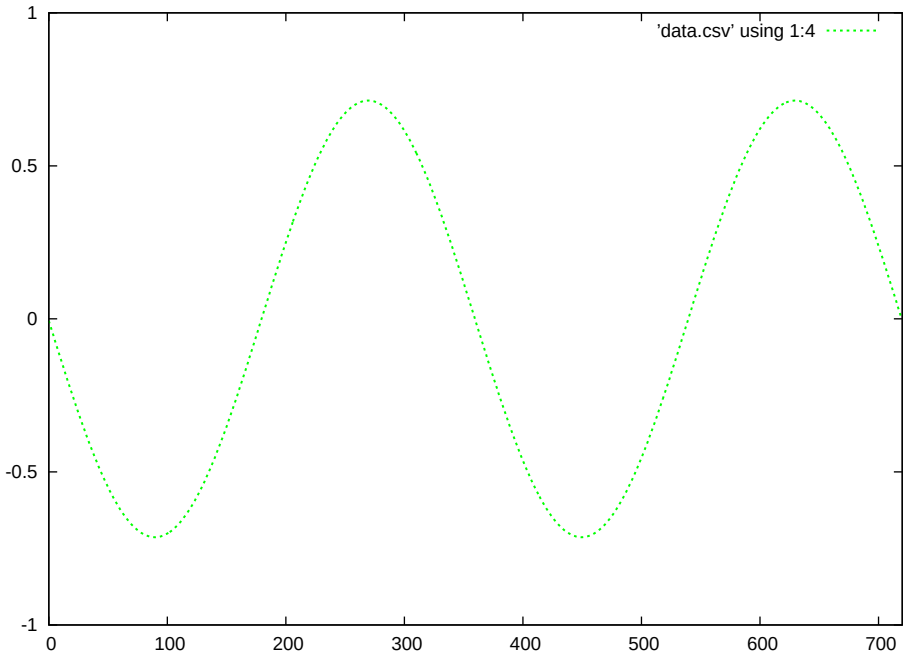
Green = standing wave



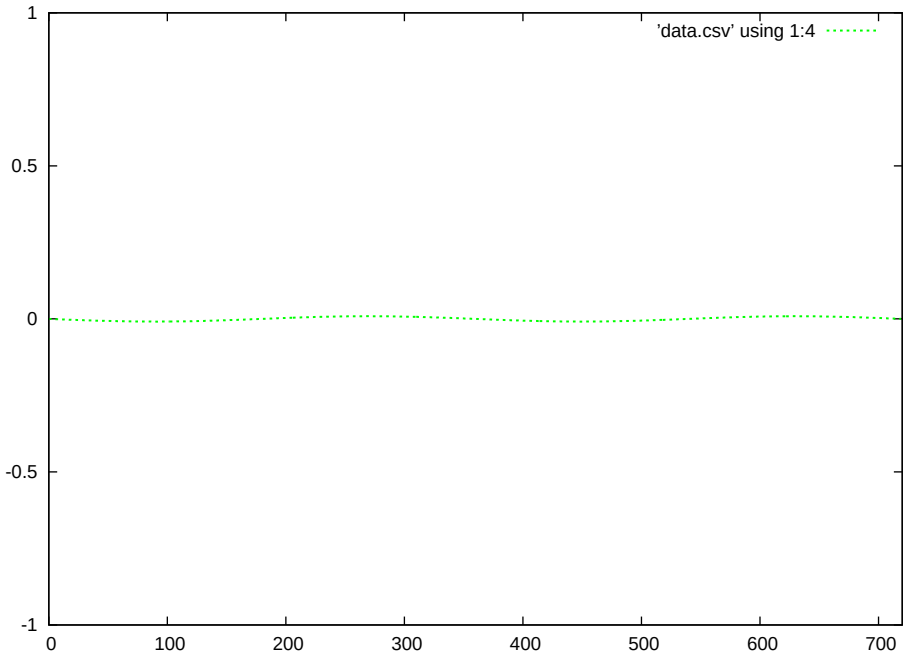
Green = standing wave



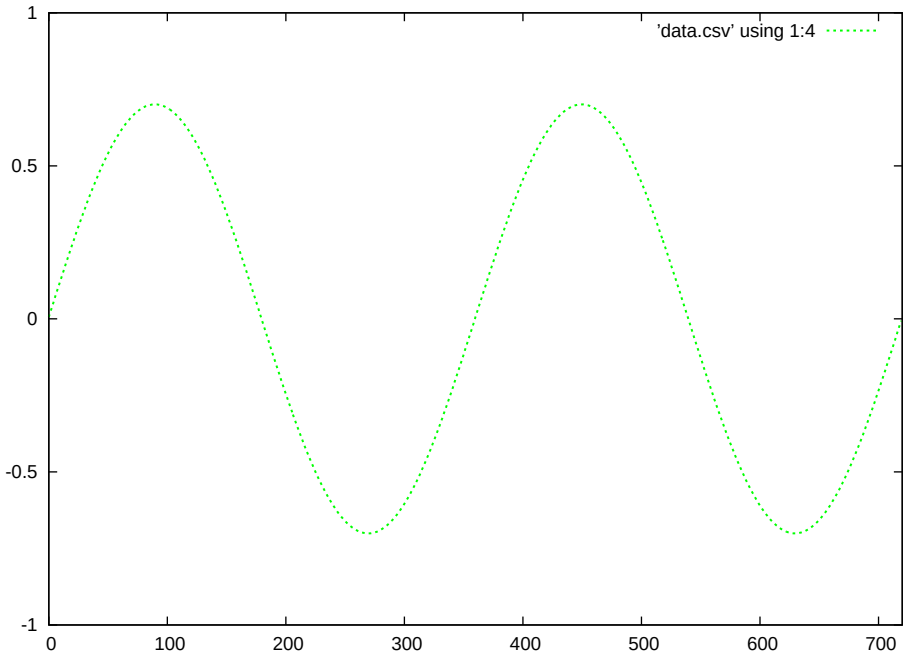
Green = standing wave



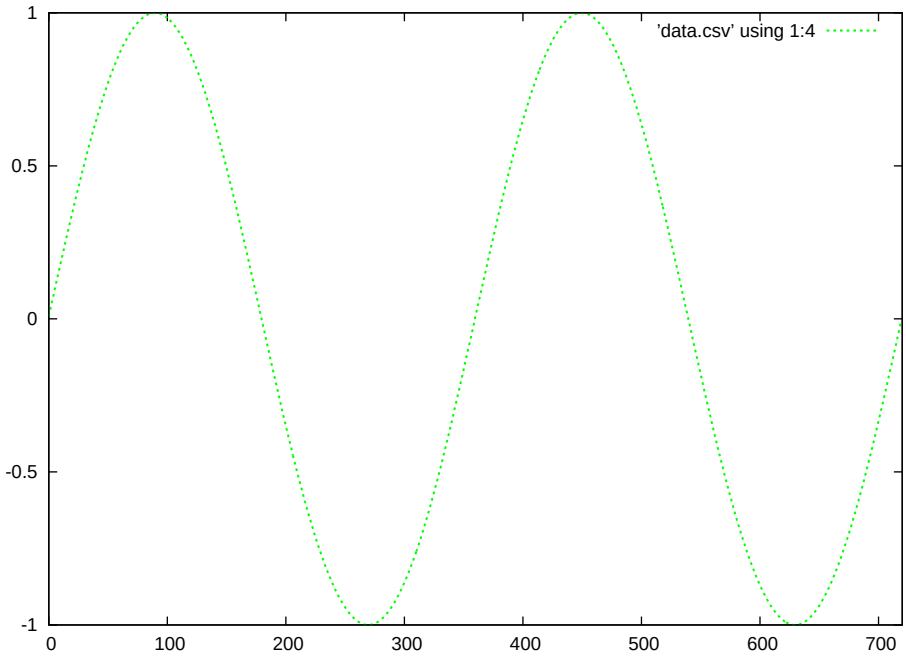
Green = standing wave



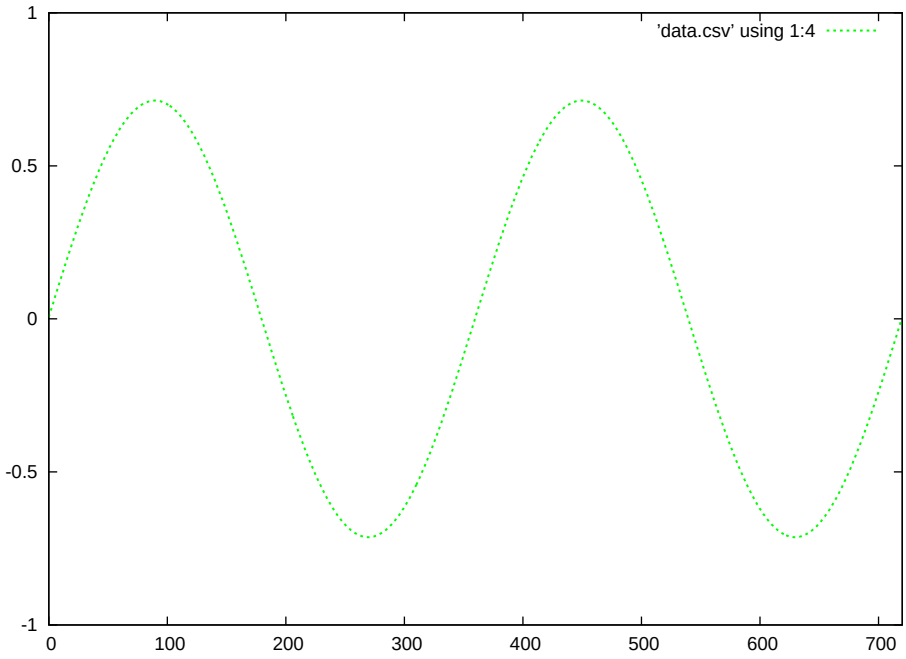
Green = standing wave



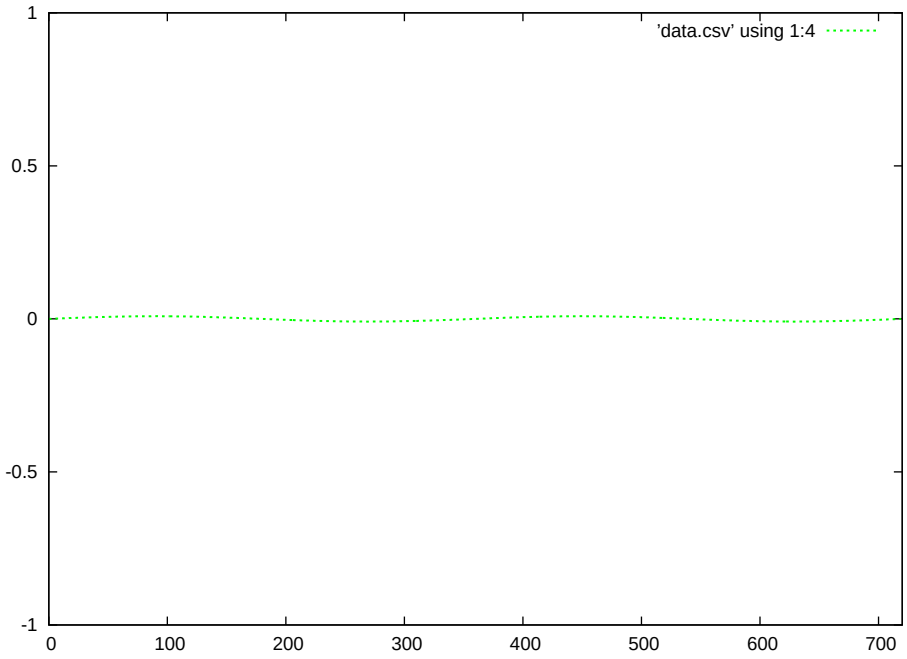
Green = standing wave



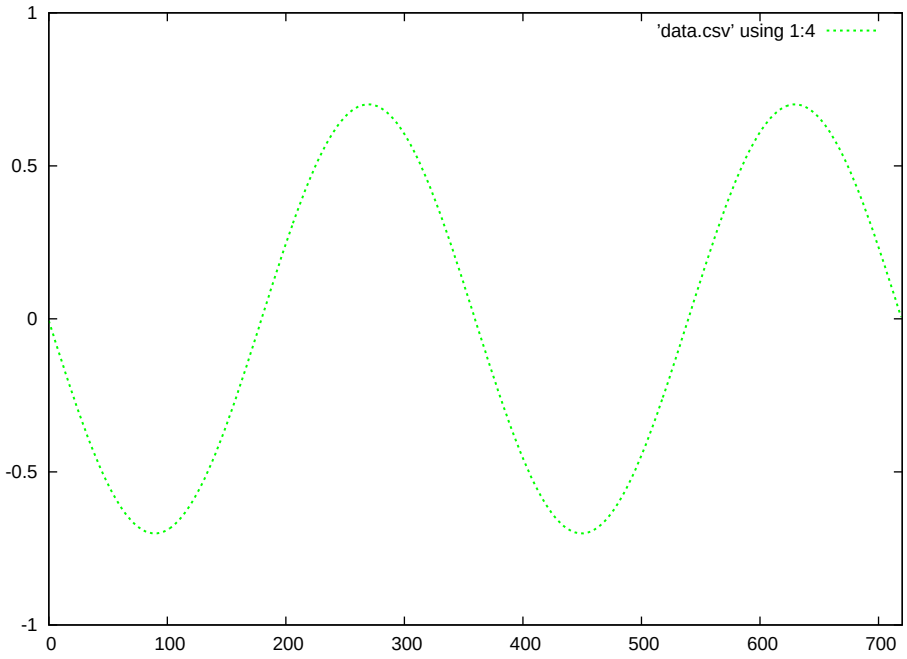
Green = standing wave



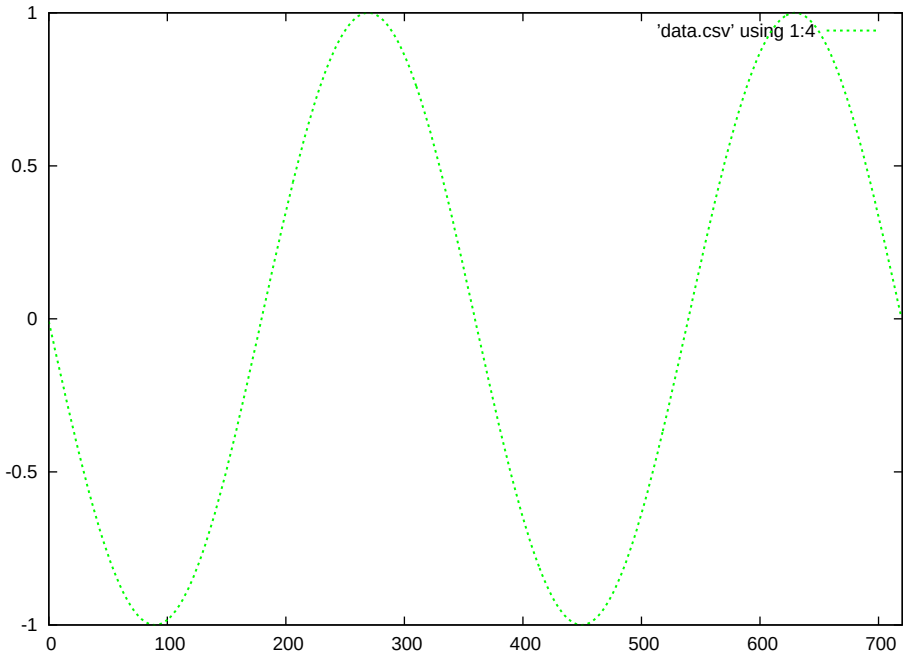
Green = standing wave



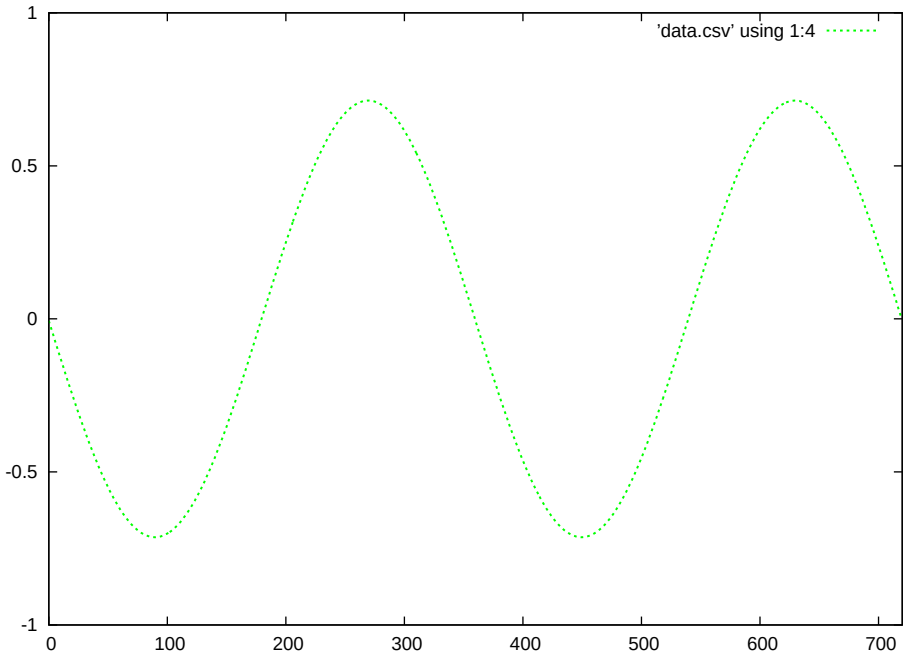
Green = standing wave



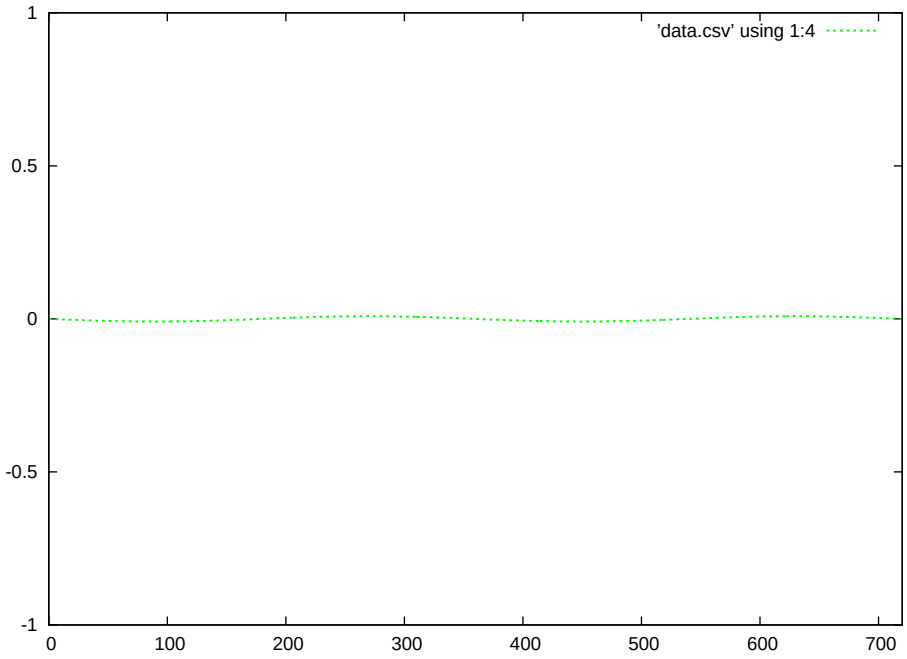
Green = standing wave



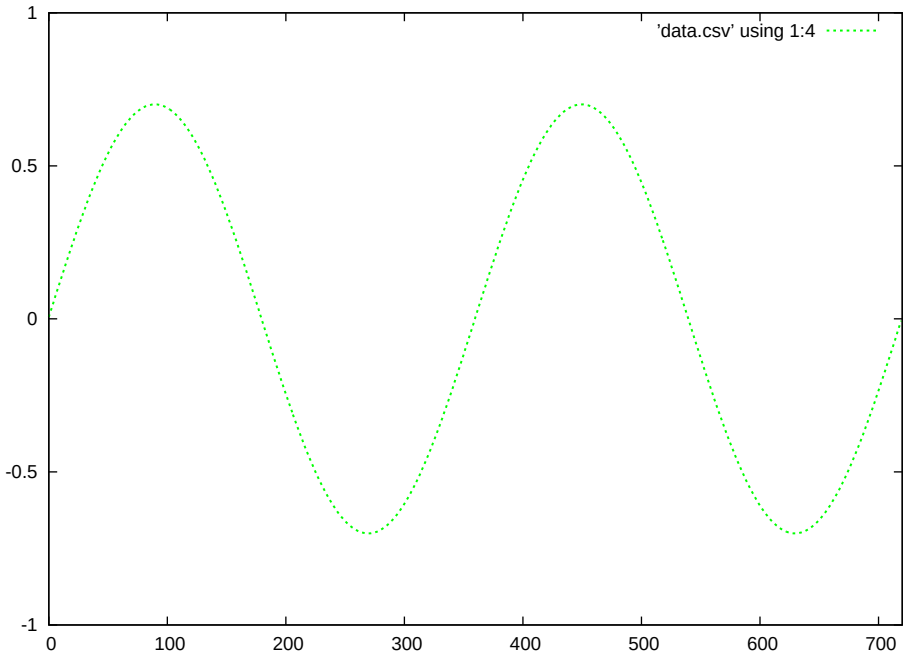
Green = standing wave



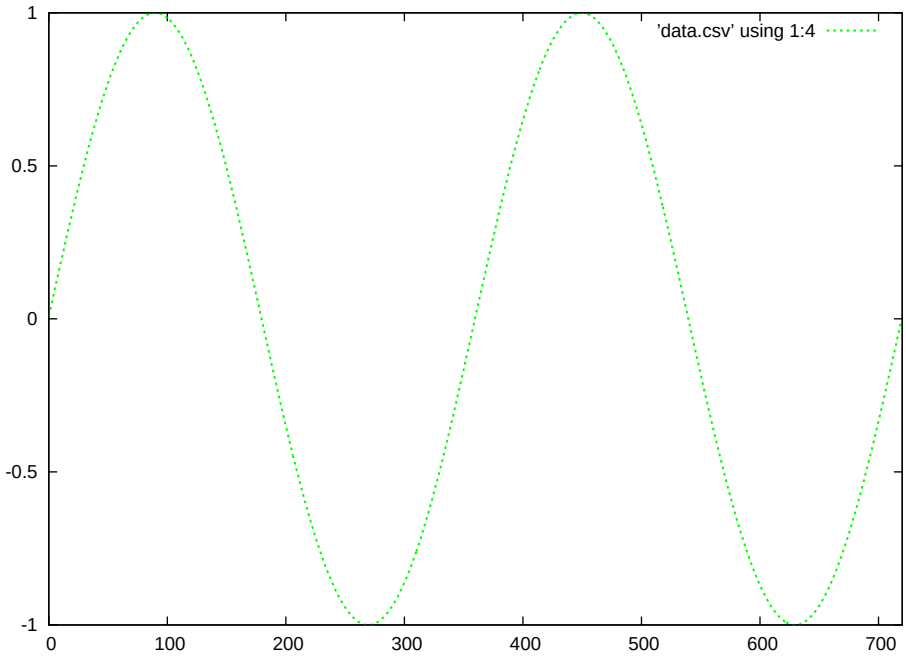
Green = standing wave



Green = standing wave



Green = standing wave



C++ source code for initial forward, reflected, and superposition waveforms

```
#include <iostream>
#include <cmath>
using namespace std;

float sinecalc (int);

int main (void)
{
  int x, offset;
  float fwd[1440];
  float ref[720];
  float sum[720];

  offset = 1440;

  for (x = 0 ; x < 1440 ; ++x)
  {
    fwd[x] = 0.5*sinecalc(x-offset);
  }

  for (x = 0 ; x < 720 ; ++x)
  {
    if (offset <= 720)
    {
      ref[x] = 0.0;
      sum[x] = 0.0;
    }

    else
    {
      ref[719-x] = -fwd[720+x];
    }
  }

  for (x = 0 ; x < 720 ; ++x)
  {
    sum[x] = fwd[x] + ref[x];
    cout << x << " , " << fwd[x] << " , " << ref[x] << " , " << sum[x] << endl;
  }

  return 0;
}
```

```
float sinecalc (int degrees)
{
  if (degrees < 0)
    return sin (degrees * M_PI / 180);

  else
    return 0.0;
}
```

Running this exact program produces a set of text-based data, separated by commas, representing the forward, reflected, and summation waves at an angle of 1440 degrees.

Gnuplot source code (named `gnuplot.txt`)

```
set datafile separator ","  # Interpret commas as field separators
set term postscript eps
set xrange [0:720]  # Sets bounds on the domain
set yrange [-1:1]  # Sets bounds on the domain
set style line 1 lw 3 lc rgb "red"  # Sets ls 1 thickness=3 color=red
set style line 2 lw 3 lc rgb "blue"  # Sets ls 2 thickness=3 color=blue
set style line 3 lw 3 lc rgb "green"  # Sets ls 3 thickness=3 color=green
set output 'anim_sw_fr_1440.eps'
plot 'data.csv' using 1:2 with lines ls 1, 'data.csv' using 1:3 with lines ls 2
set output 'anim_sw_sum_1440.eps'
plot 'data.csv' using 1:4 with lines ls 3
```

Note: the C++ program when compiled and run outputs comma-separated value (CVS) to the console (standard output). That C++ program must be compiled and run over and over again, each time with a different `offset` value representing the number of degrees the two waveforms have evolved over. For each run of the C++ program, I used Gnuplot to convert the comma-separated text file into graphical images, editing the gnuplot script each time to re-name the files according to the offset (angle) value. To convert this text data into graphical plots, you must redirect the output to a file (I use the filename `data.csv`) like this:

```
./a.out > data.csv
```

Then, you invoke Gnuplot to convert this text data into two Encapsulated PostScript files like so:

```
gnuplot -p gnuplot.txt
```

Gnuplot must be run once per execution of the C++ code, each time producing a pair of graphical images. The first image shows both the forward and reflected waves at that angle (`offset`), and the second image showing just the summation of the forward and reflected waves at that angle.

C++ source code for established standing waveform

```
#include <iostream>
#include <cmath>
using namespace std;

float sinecalc (int);

int main (void)
{
  int x, offset;
  float fwd[720];
  float ref[720];
  float sum[720];

  offset = 360;

  for (x = 0 ; x < 720 ; ++x)
  {
    fwd[x] = 0.5*sinecalc(x+offset);
    ref[719-x] = -0.5*sinecalc(x+offset);
  }

  for (x = 0 ; x < 720 ; ++x)
  {
    sum[x] = fwd[x] + ref[x];
  }

  for (x = 0 ; x < 720 ; ++x)
  {
    cout << x << " , " << fwd[x] << " , " << ref[x] << " , " << sum[x] << endl;
  }

  return 0;
}

float sinecalc (int degrees)
{
    return sin (degrees * M_PI / 180);
}
```

As before, this C++ code must be compiled and executed repeatedly, each time with a different offset value. The only difference here is that the offset values need only span from 0 to 360 degrees,

not all the way to 1440 degrees as before to simulate the initial travel of both the forward and reflected waves along the transmission line's length.

5.2 Animation of a standing wave with 50% reflection

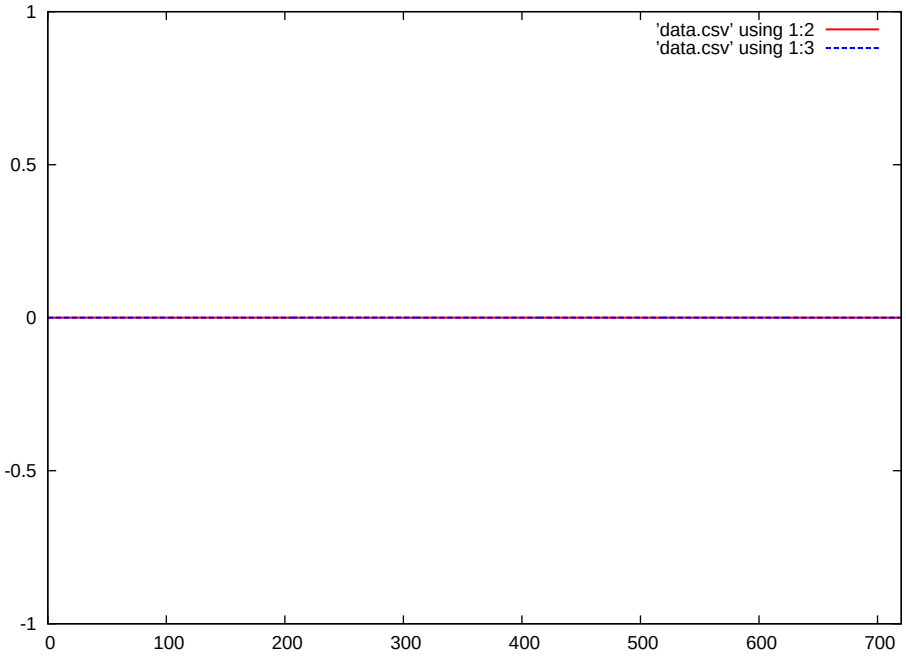
This series of animations shows waveforms traveling along a transmission line, the incident (or "forward") waveform shown in red and the reflected waveform shown in blue. It is assumed that the signal source is on the left-hand side of the graph, while the transmission line terminates on the right-hand side of the graph.

If the transmission line is terminated in such a way as to reflect 50% of the forward waveform at its end, the reflected wave will have half the amplitude as the forward wave at the line's end but negative in value. This represents the state of affairs for waves at the end of a transmission line terminated in a resistance that is half that of the line's characteristic impedance.

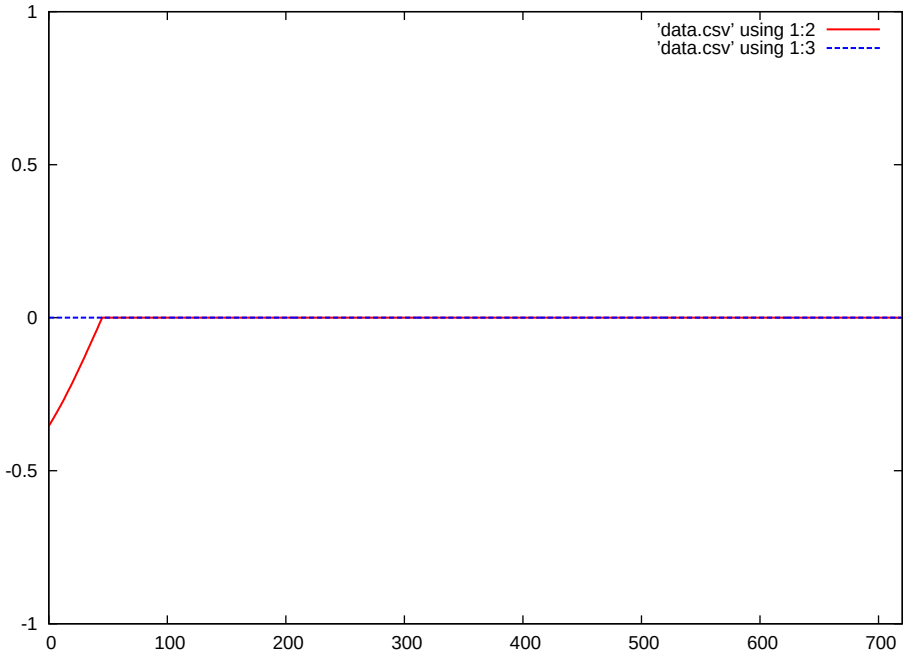
In the following flip-book animations, the first animation shows only the forward and reflected waves along the line for 1440 degrees of rotation. The second animation shows this same sequence of forward and reflected waves, but in an adjacent image shows the superposition of these two waveforms in a different color. The third animation shows that same superposition, but after the forward and reflected waves have traveled the full length of the transmission line to create an established "standing wave" along the line.

Standing wave ratio or *SWR* for any transmission line is defined as the maximum amplitude of the superposition wave divided by its minimum amplitude. In this case, where the superposition of the forward and reflected waves varies from 75% to 25% of full scale, yielding a 3:1 SWR. You will also see how with imperfect reflection the "standing wave" doesn't quite "stand" in one place as it does when the reflected signal is just as strong as the forward signal.

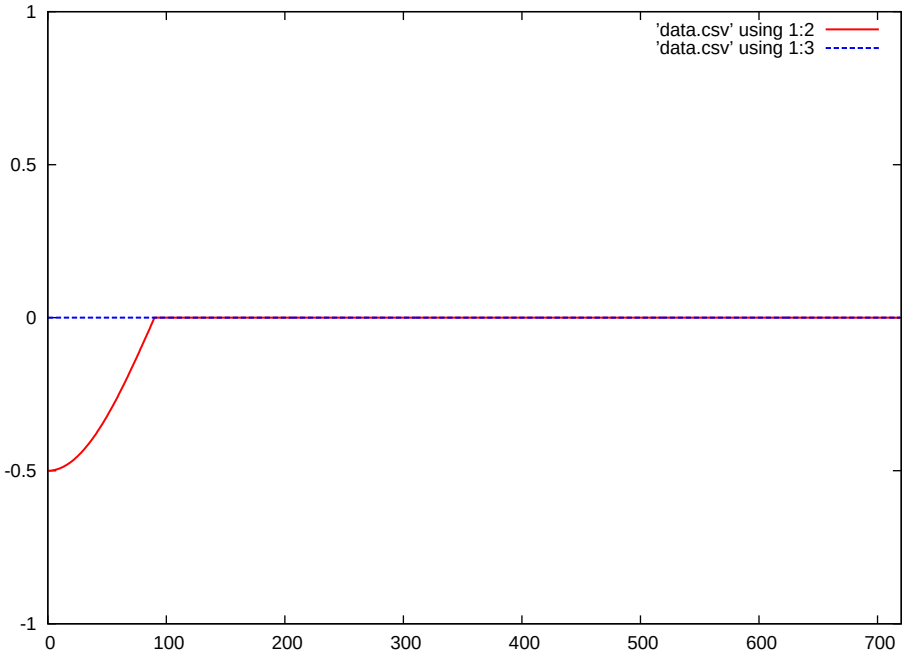
Red = forward wave Blue = reflected wave



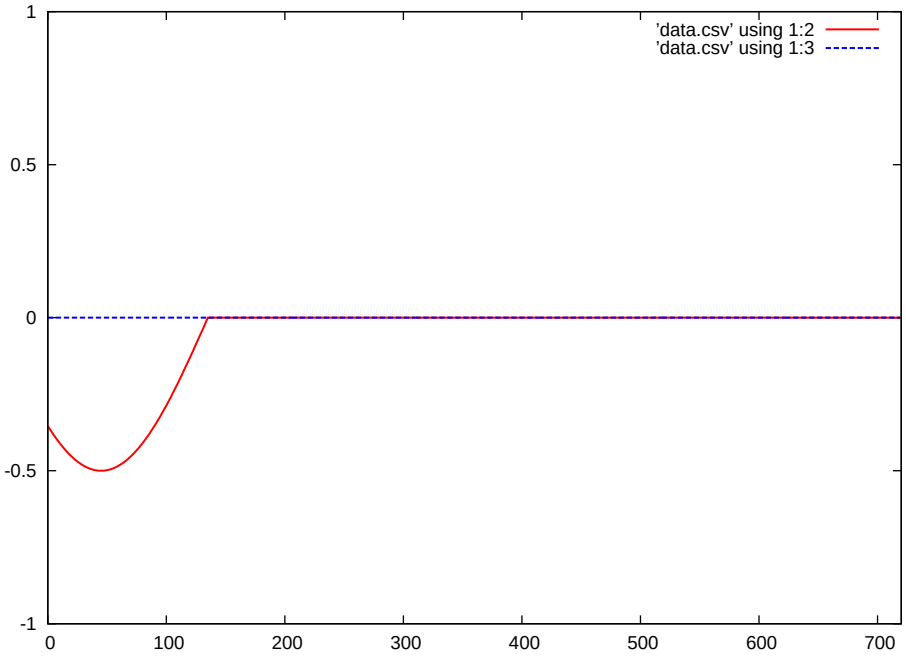
Red = forward wave Blue = reflected wave



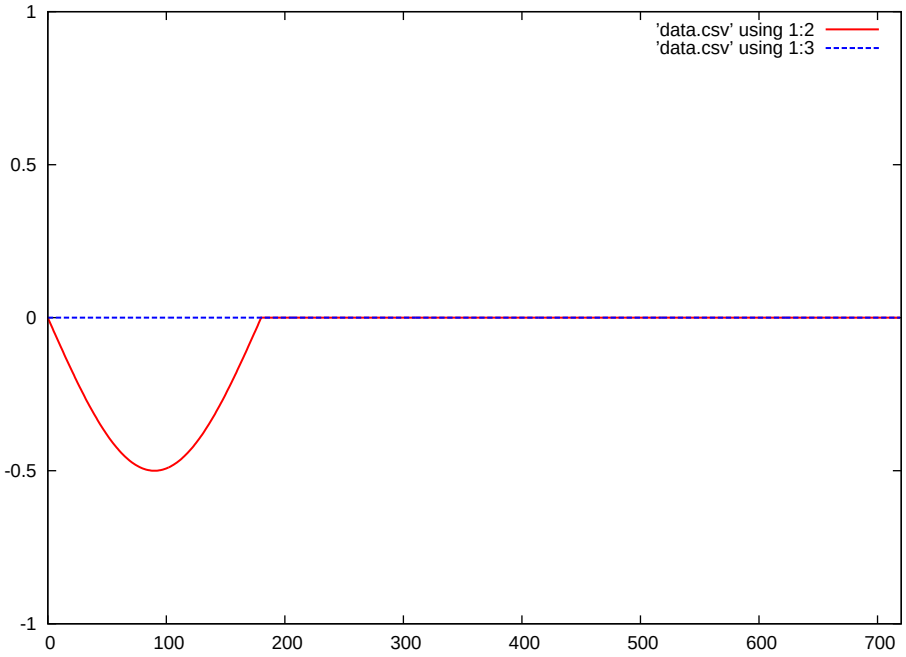
Red = forward wave Blue = reflected wave



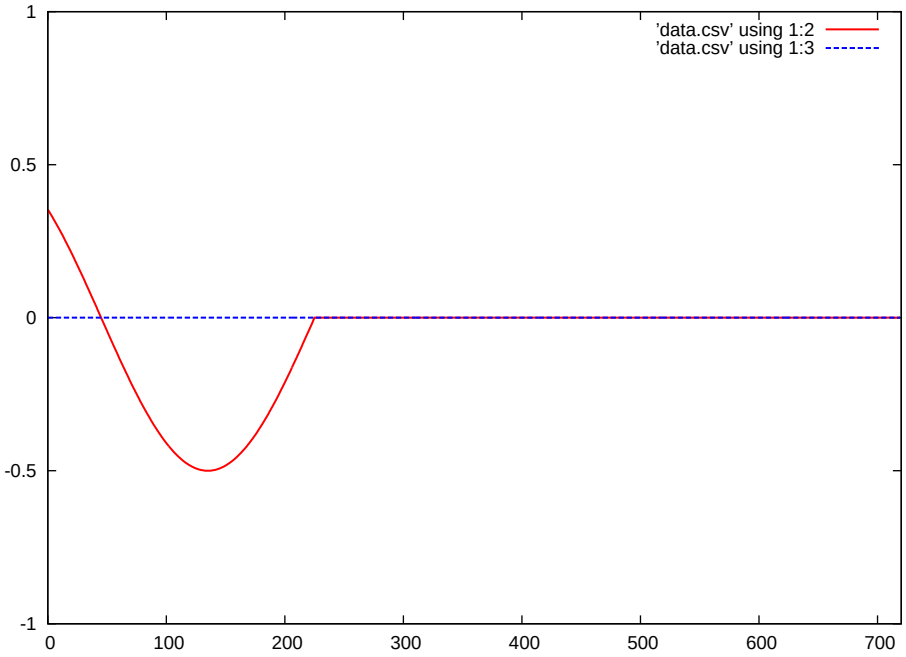
Red = forward wave Blue = reflected wave



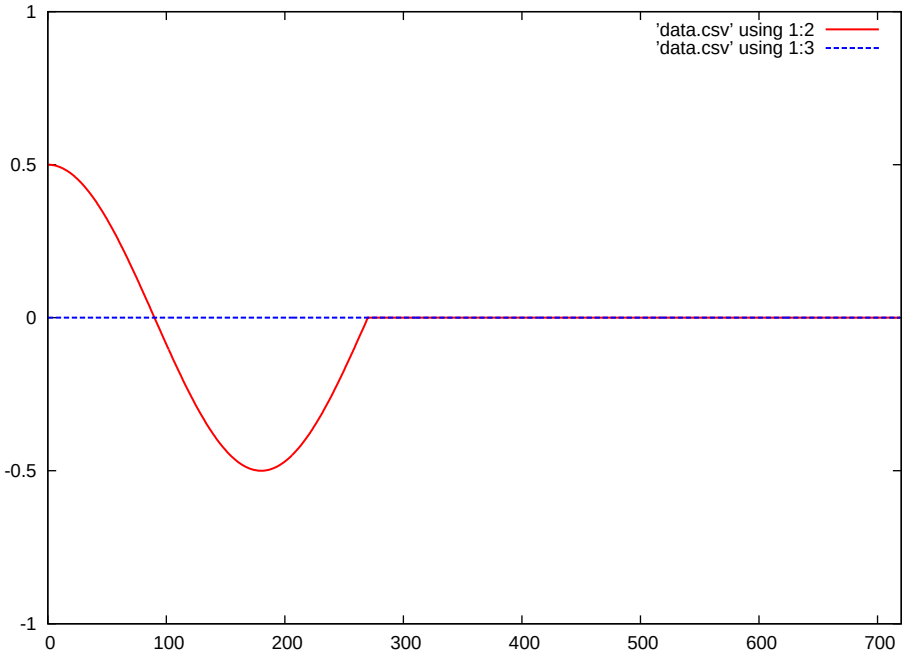
Red = forward wave Blue = reflected wave



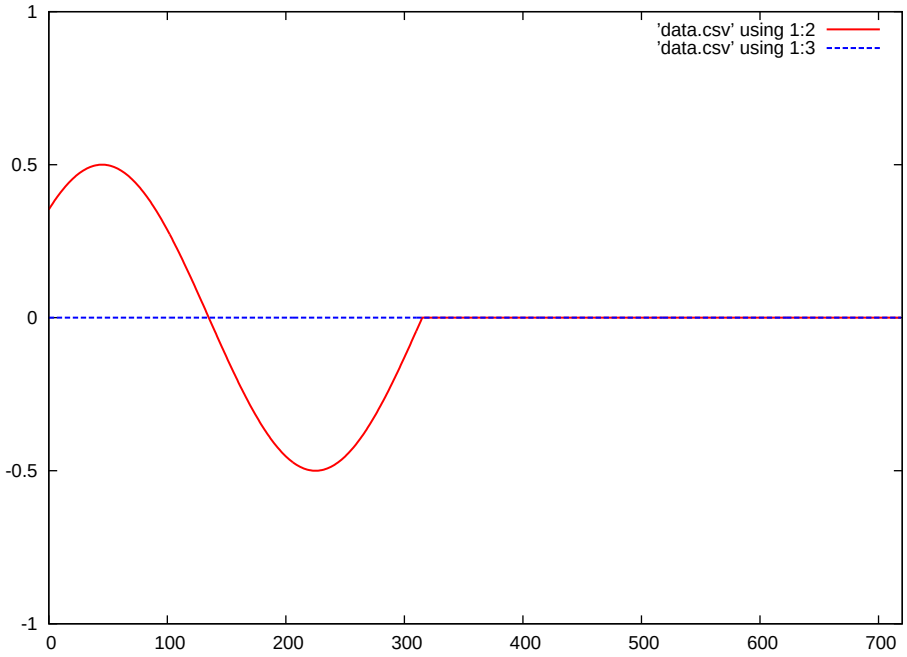
Red = forward wave Blue = reflected wave



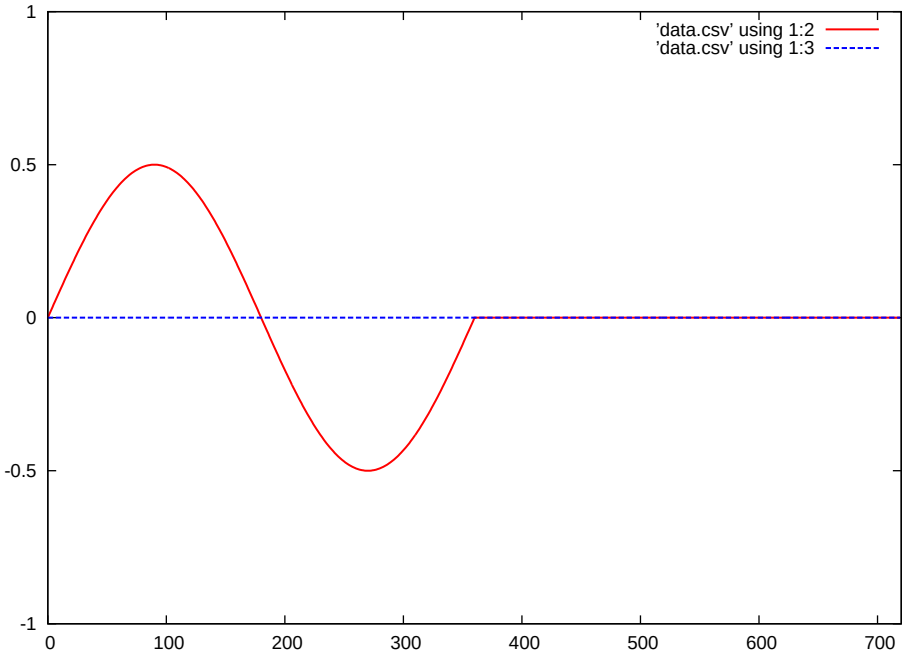
Red = forward wave Blue = reflected wave



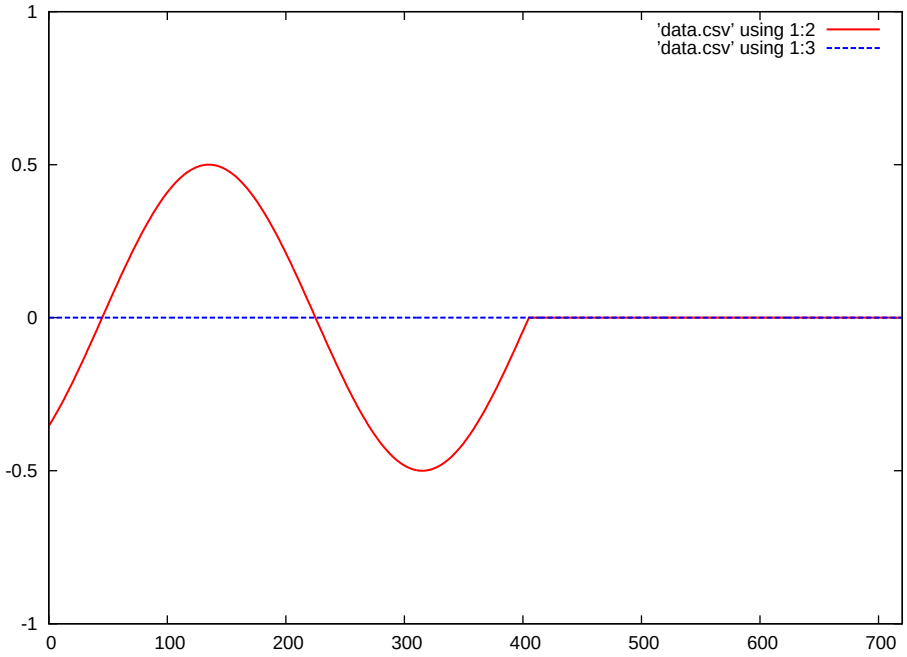
Red = forward wave Blue = reflected wave



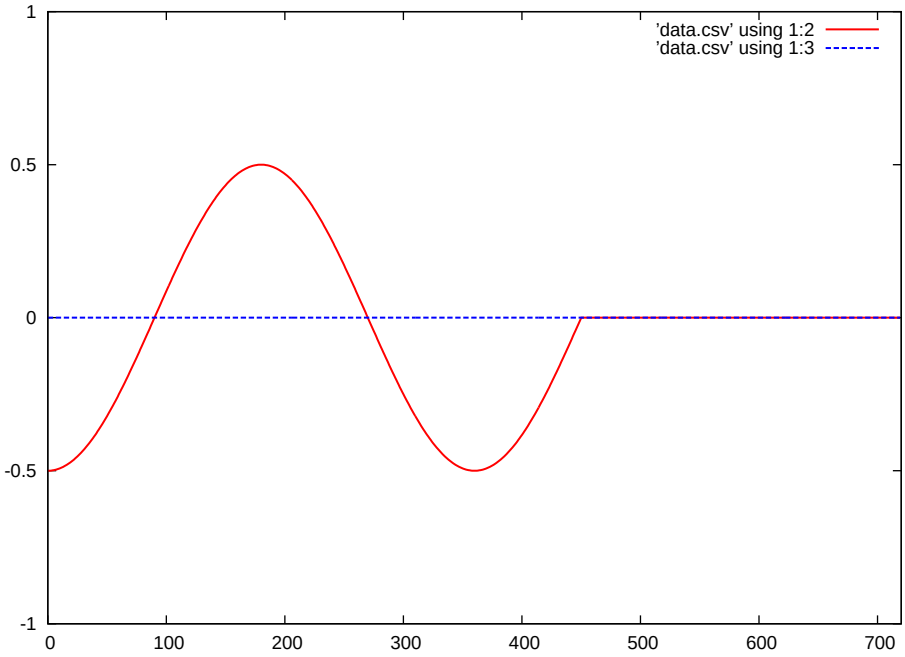
Red = forward wave Blue = reflected wave



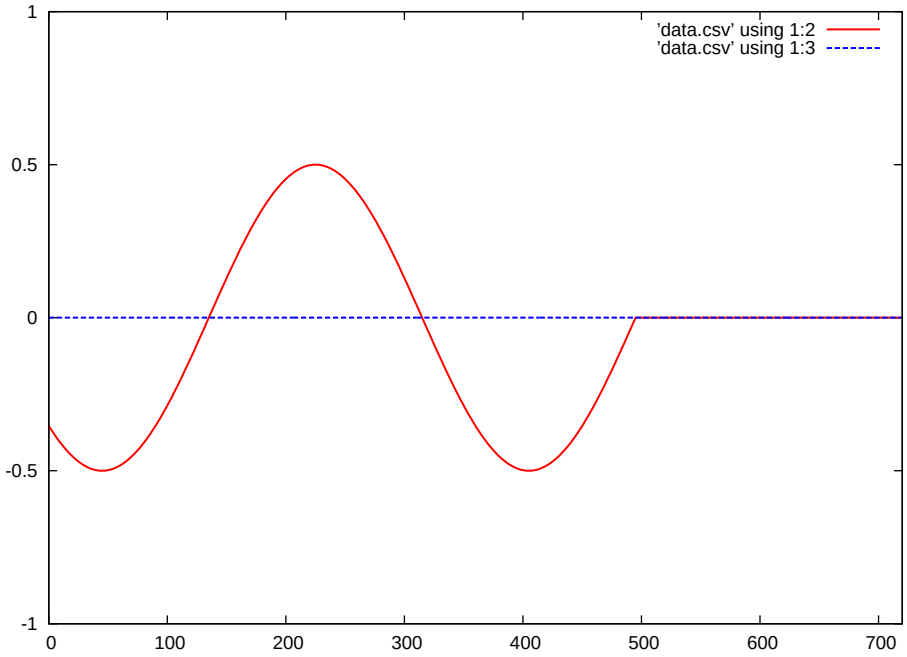
Red = forward wave Blue = reflected wave



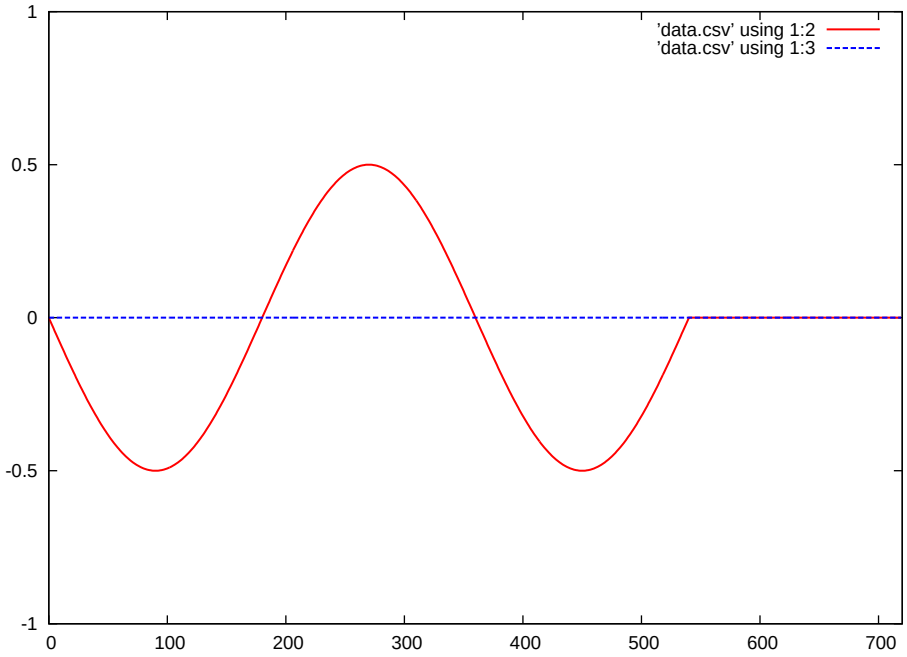
Red = forward wave Blue = reflected wave



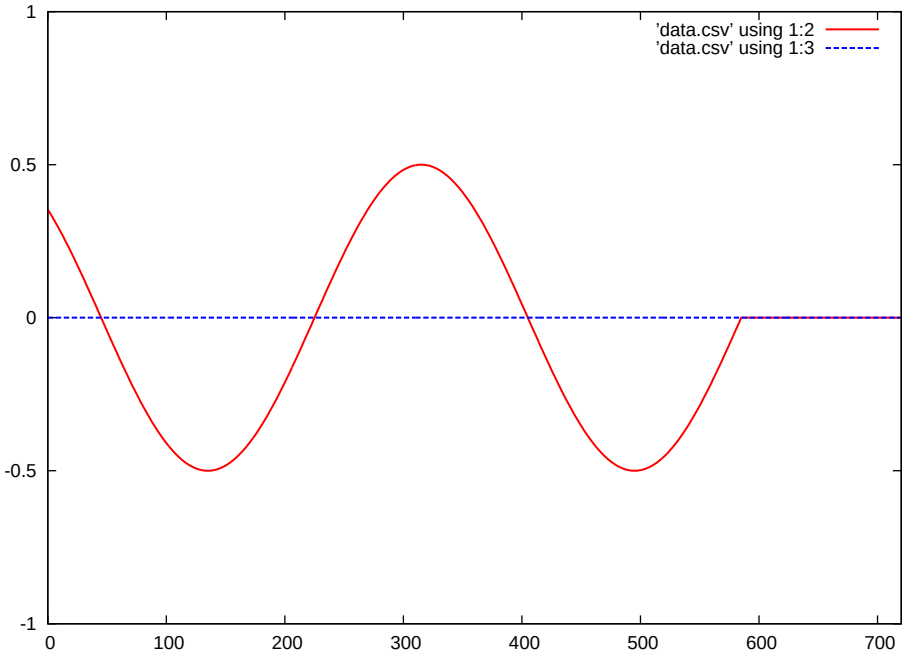
Red = forward wave Blue = reflected wave



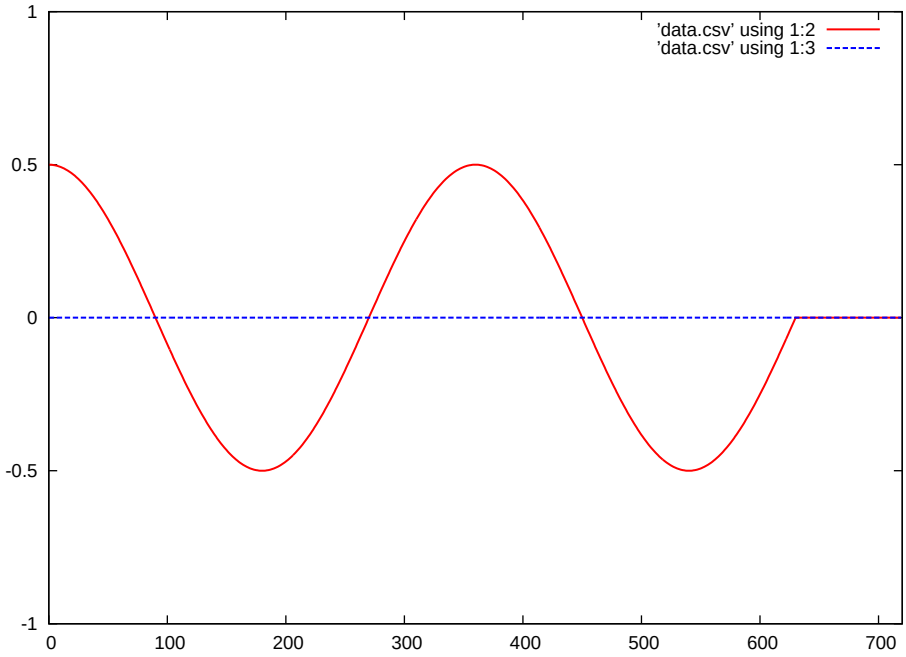
Red = forward wave Blue = reflected wave



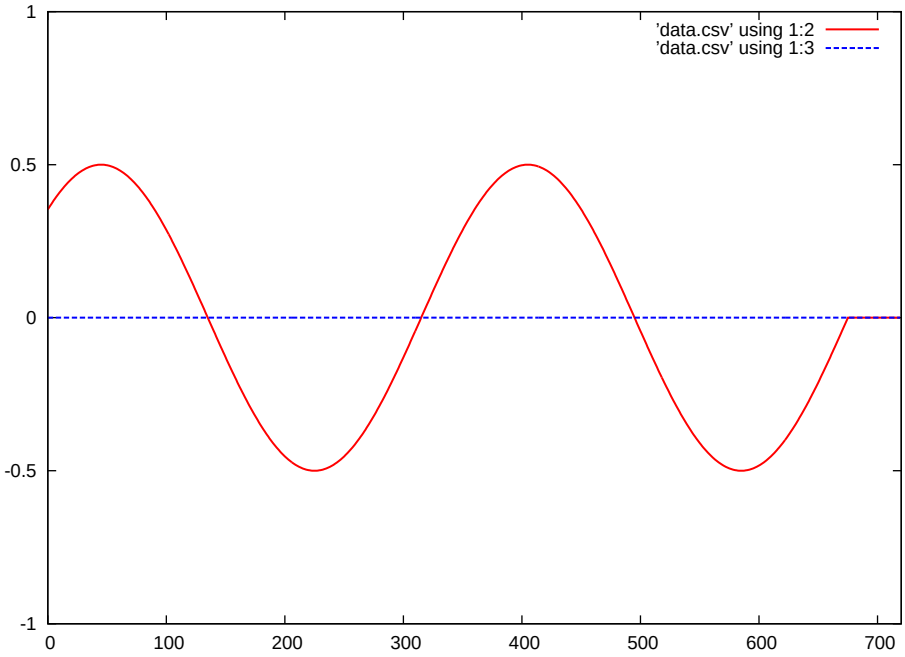
Red = forward wave Blue = reflected wave



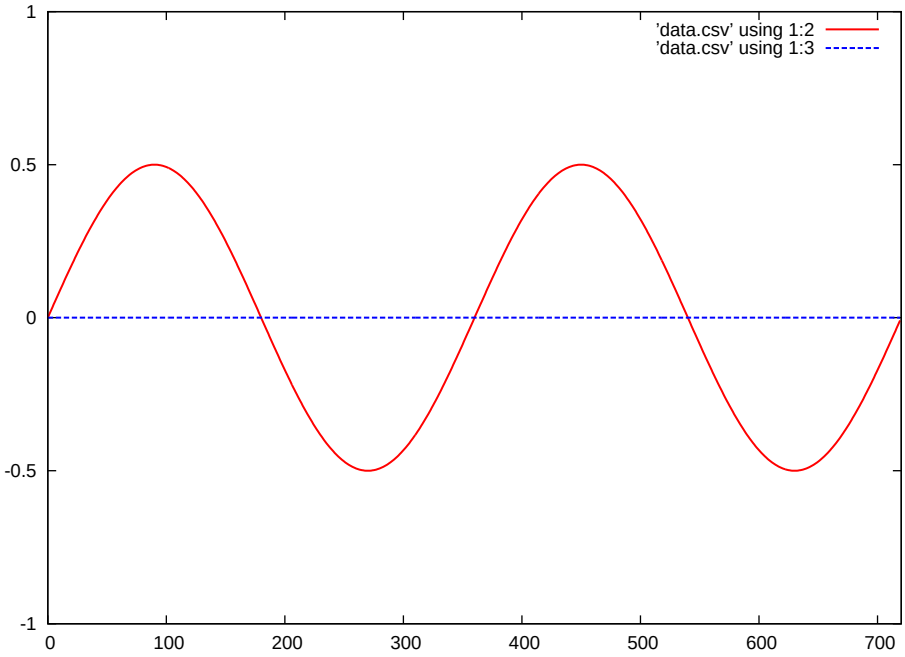
Red = forward wave Blue = reflected wave



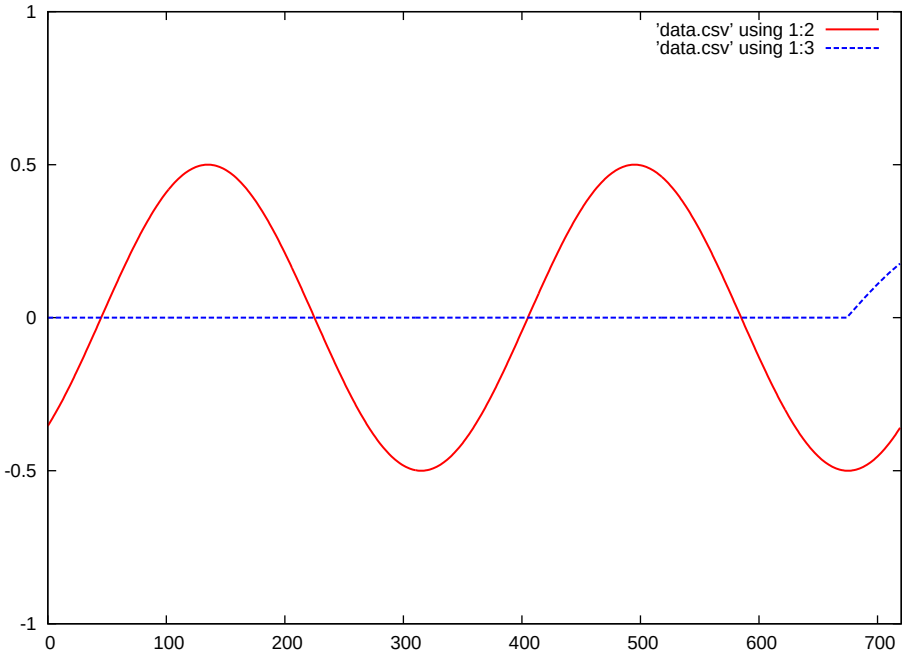
Red = forward wave Blue = reflected wave



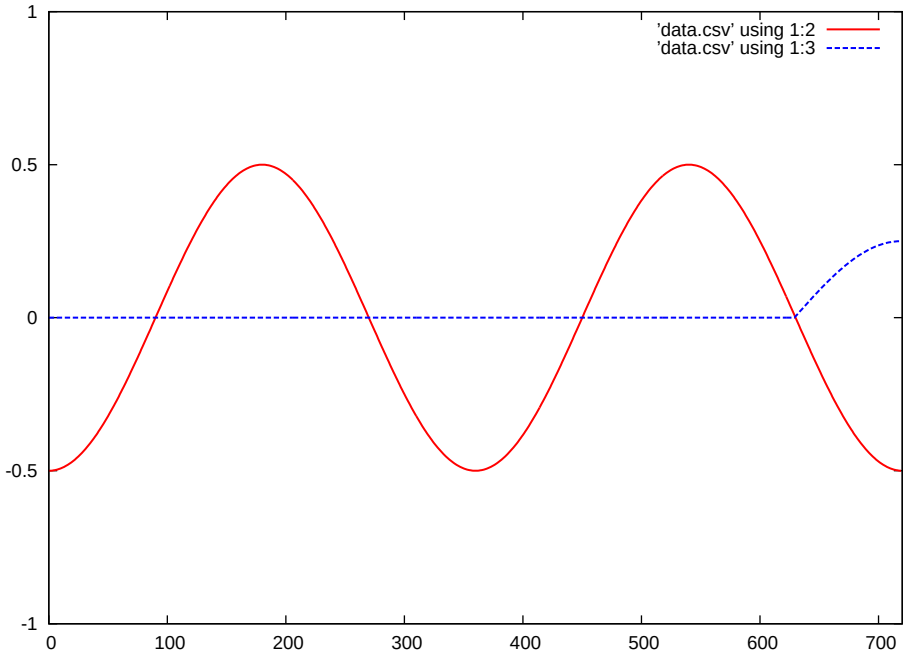
Red = forward wave Blue = reflected wave



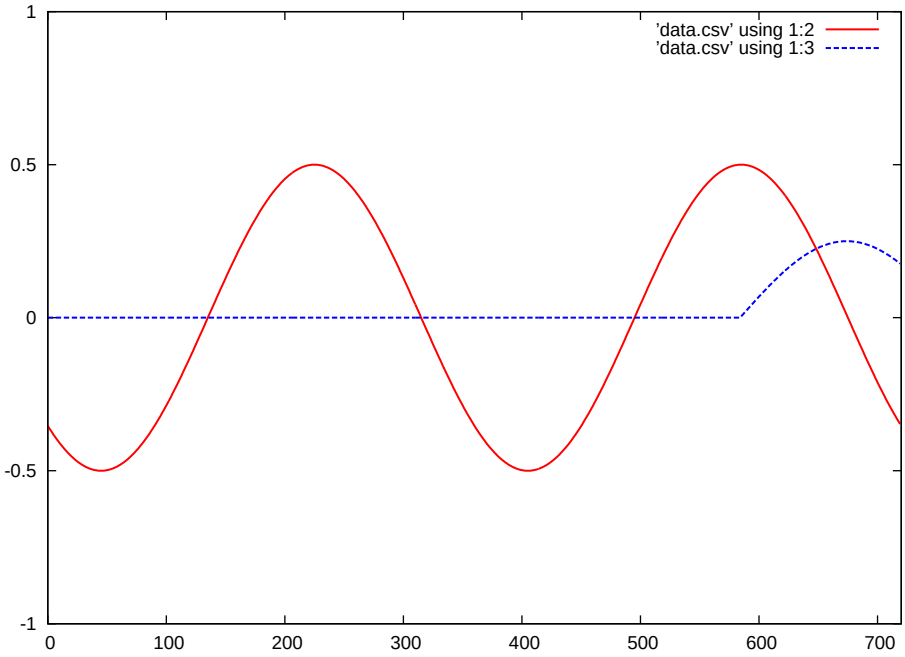
Red = forward wave Blue = reflected wave



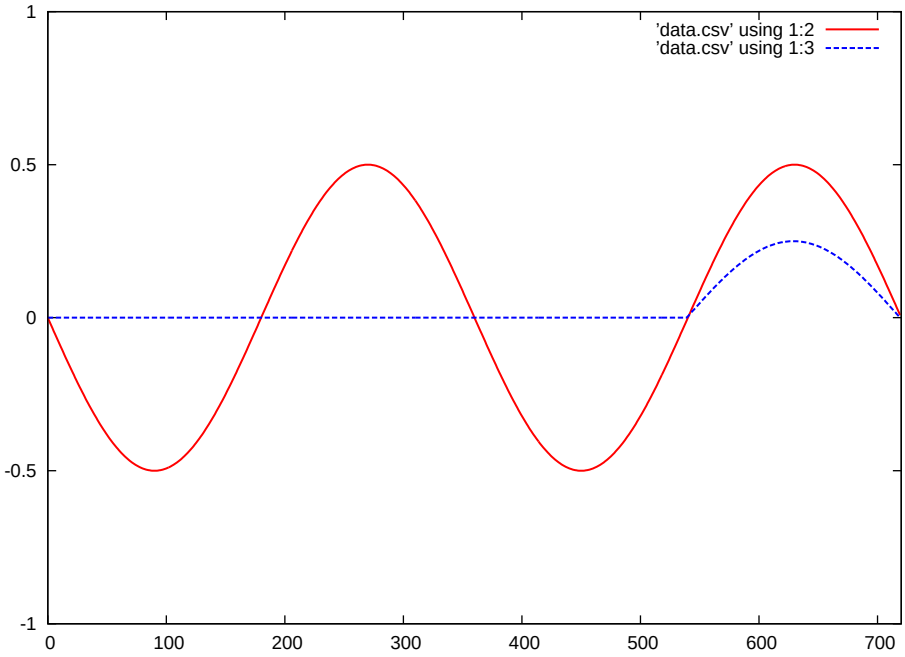
Red = forward wave Blue = reflected wave



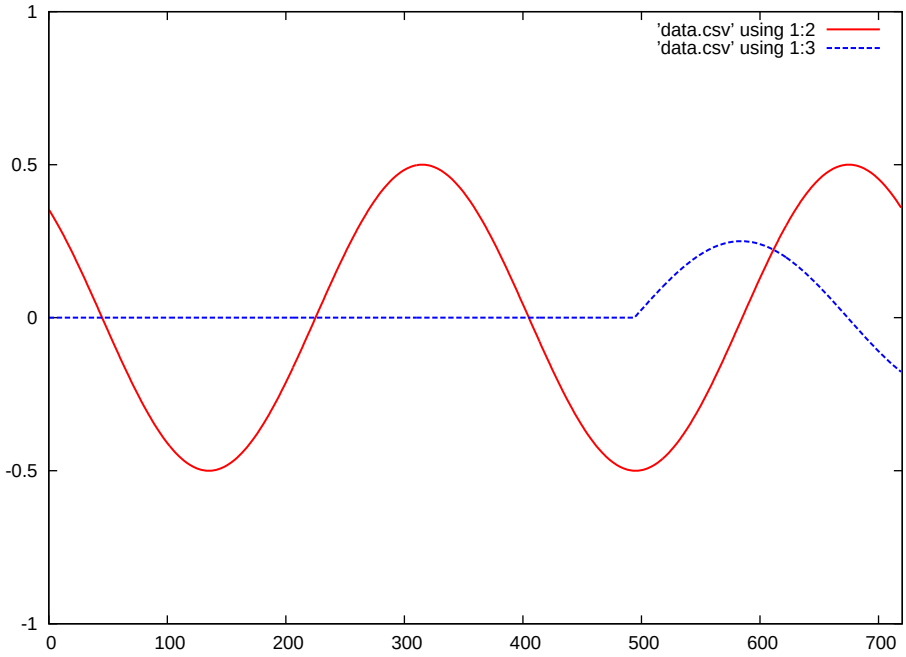
Red = forward wave Blue = reflected wave



Red = forward wave Blue = reflected wave



Red = forward wave Blue = reflected wave



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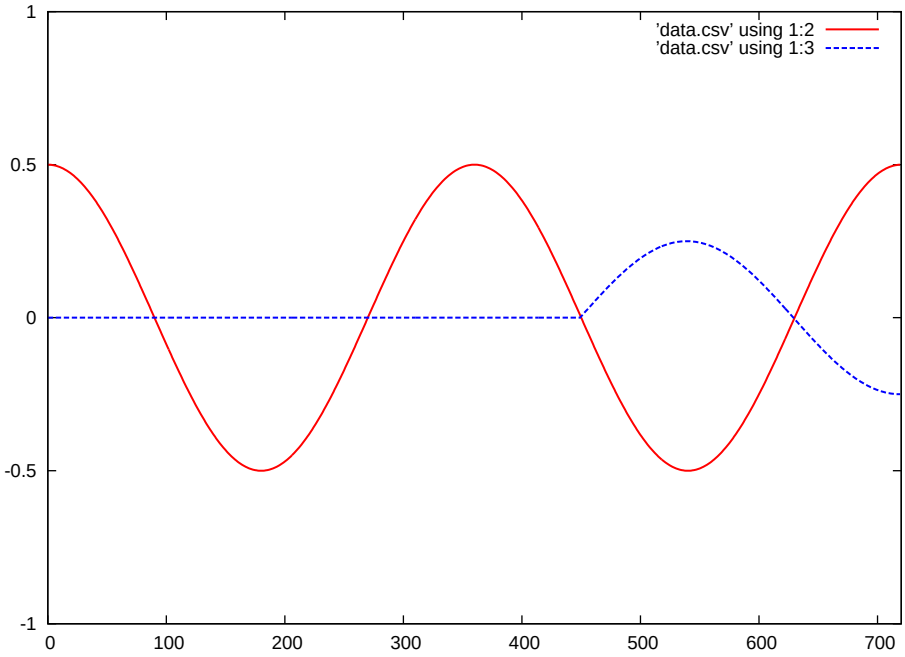

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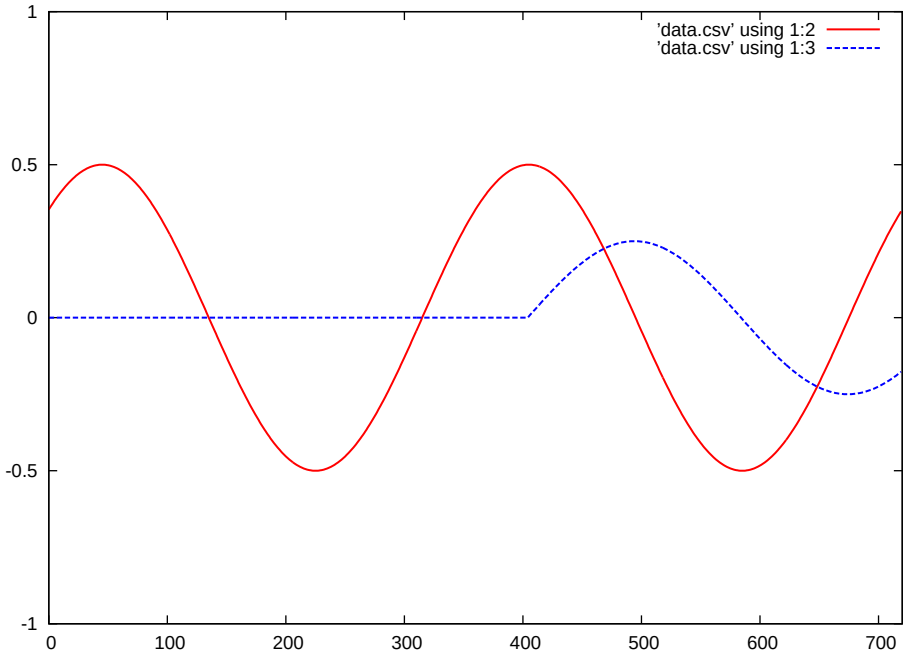

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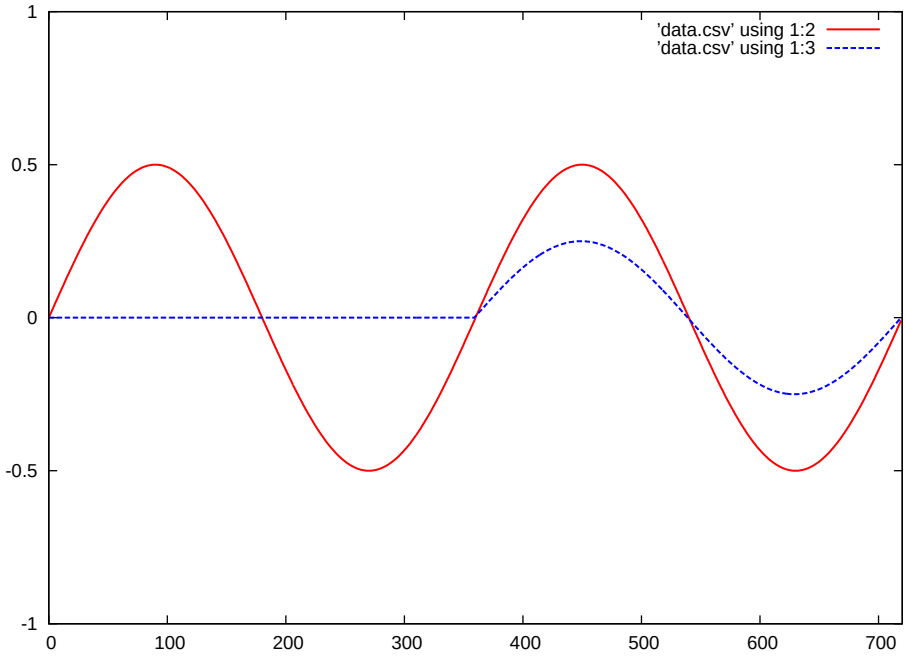

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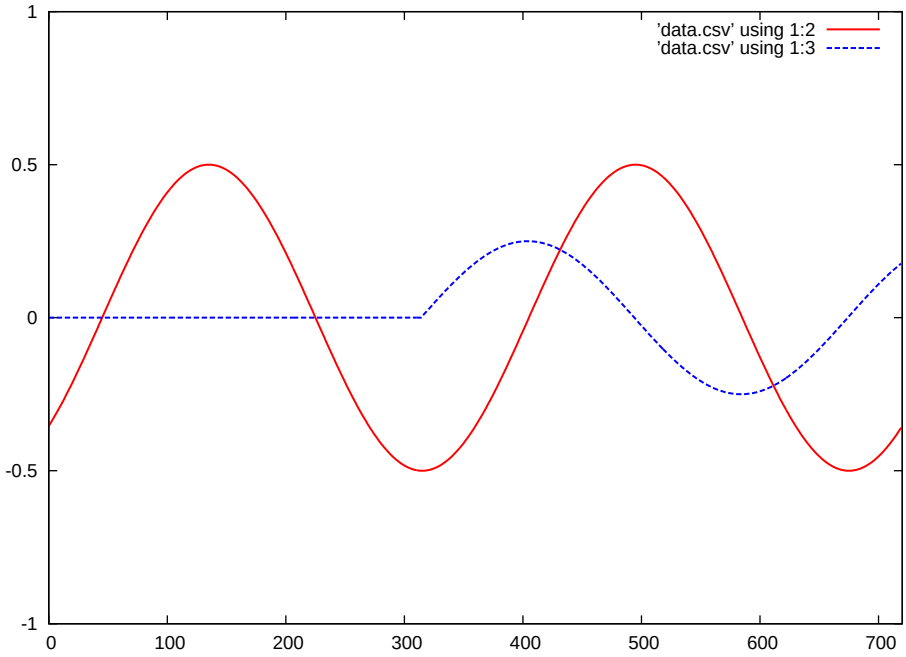

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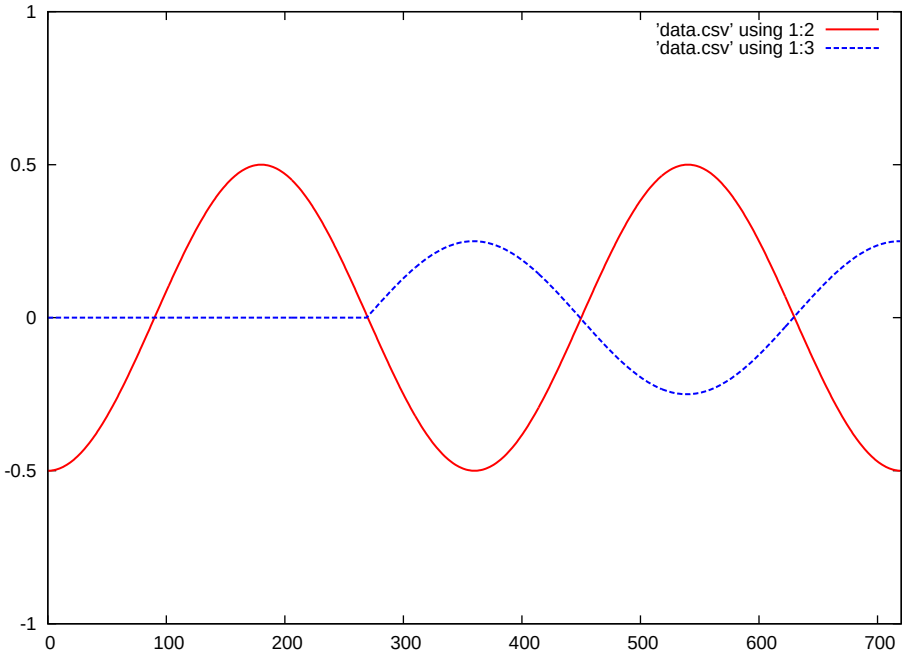

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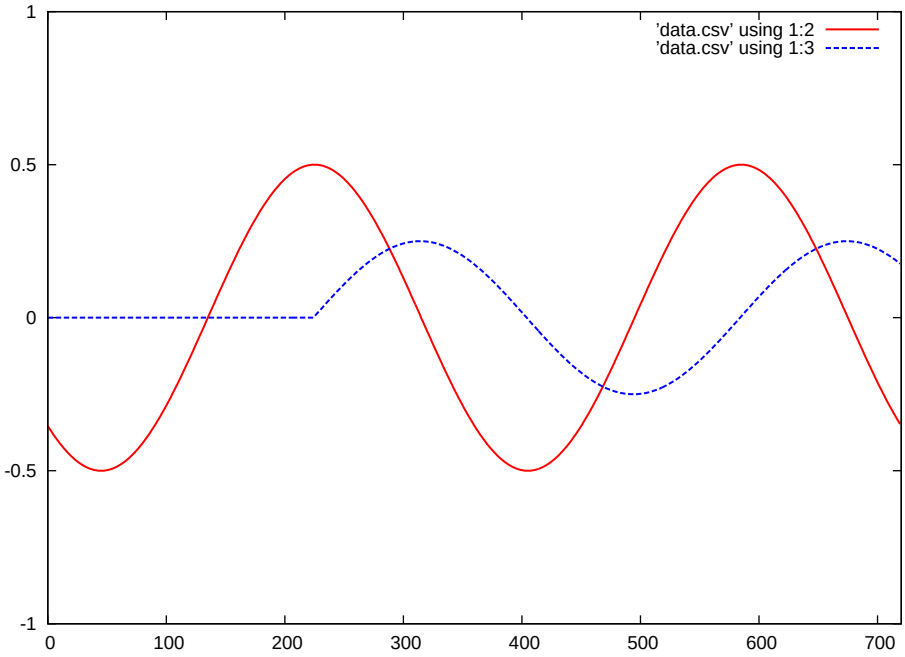

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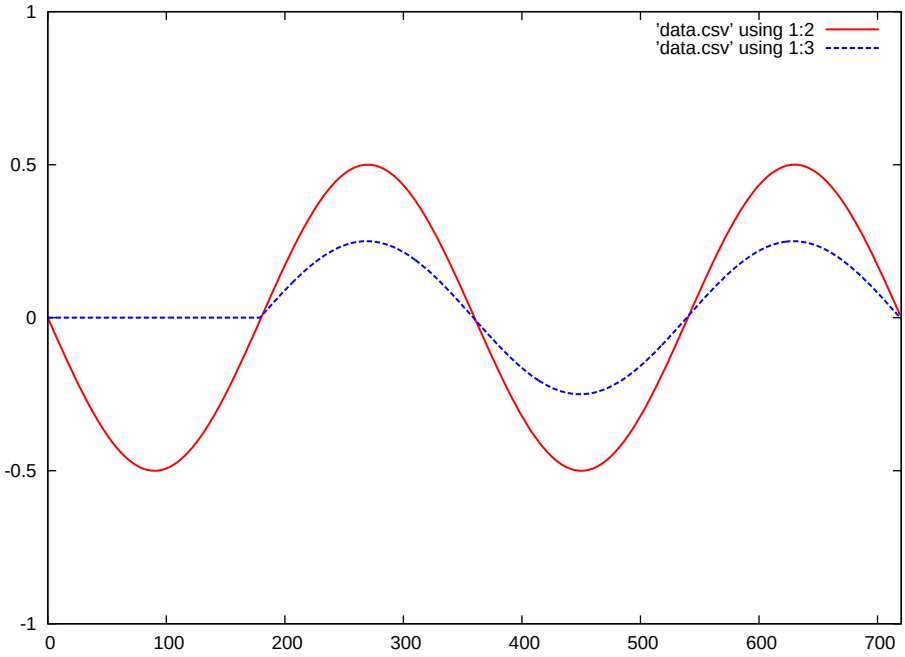

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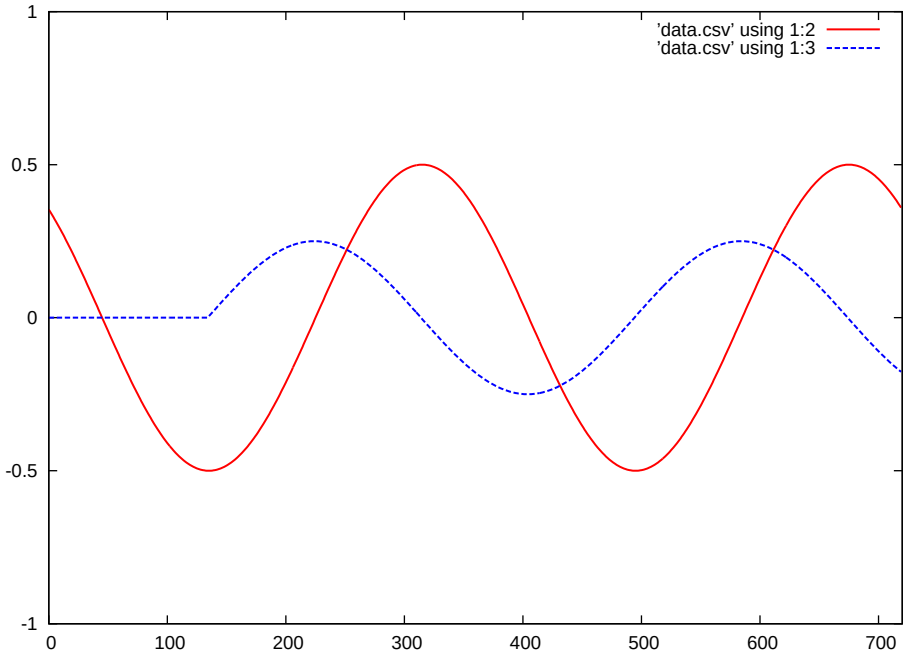

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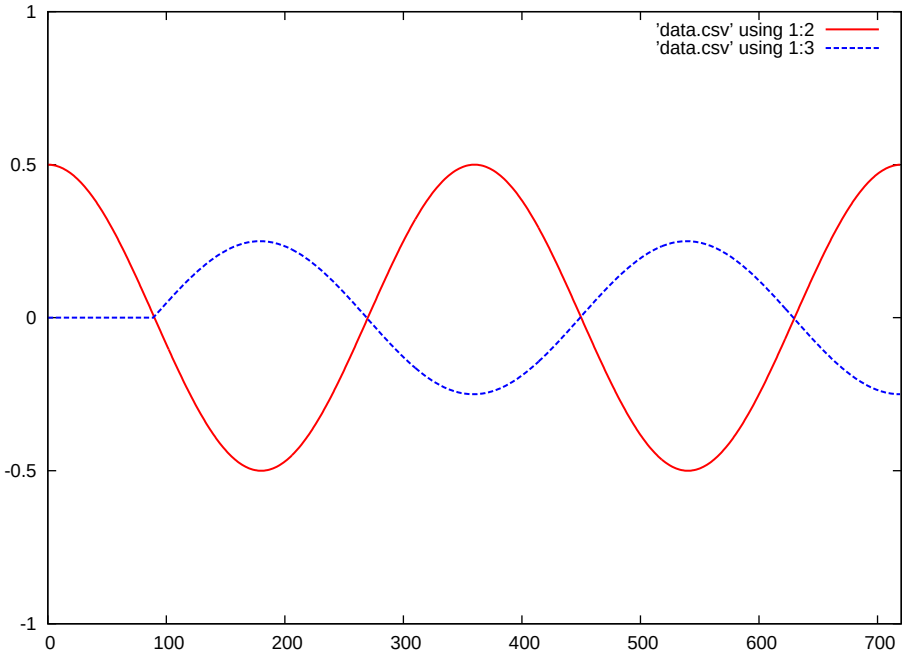

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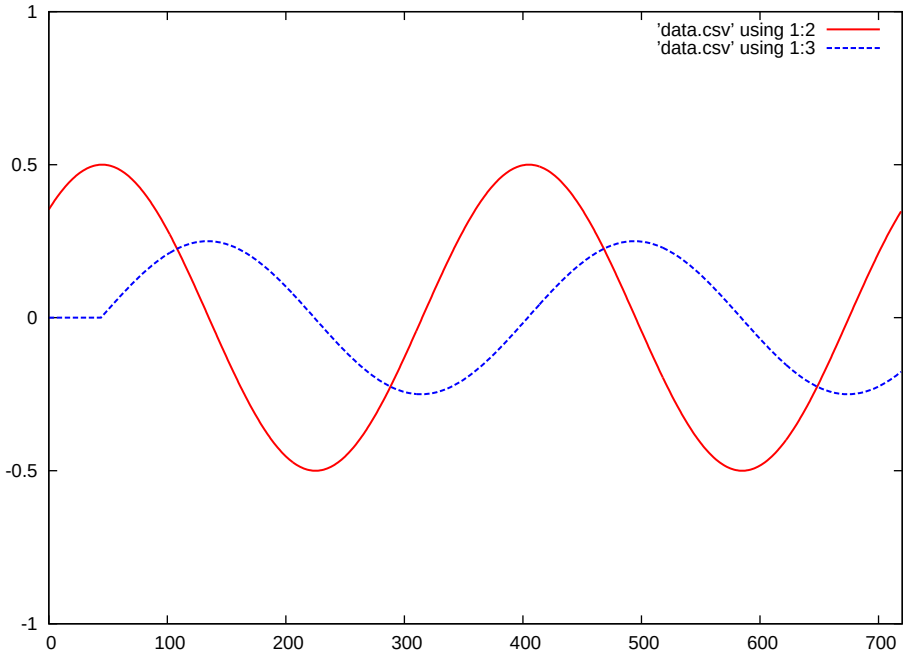

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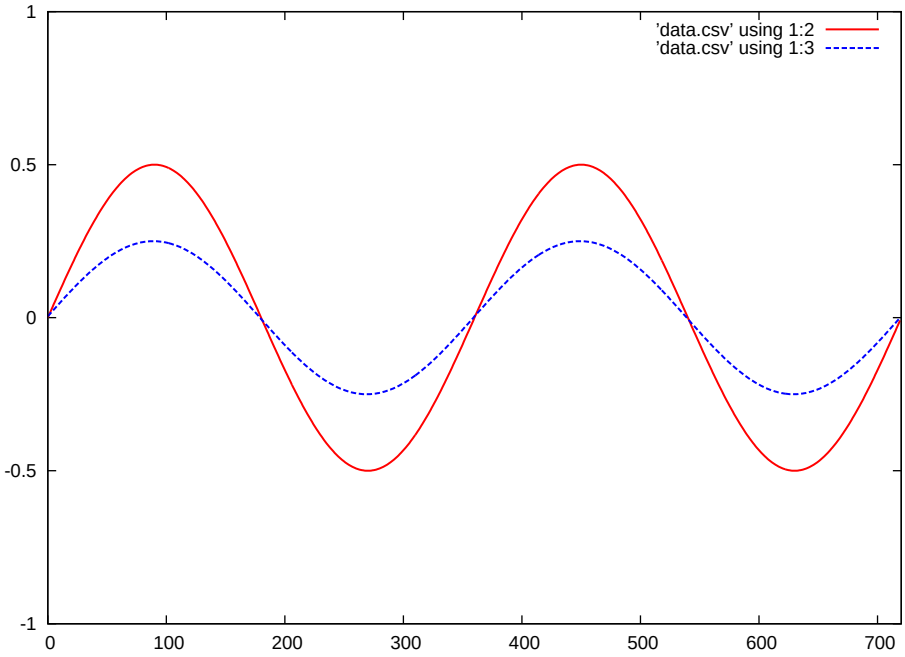
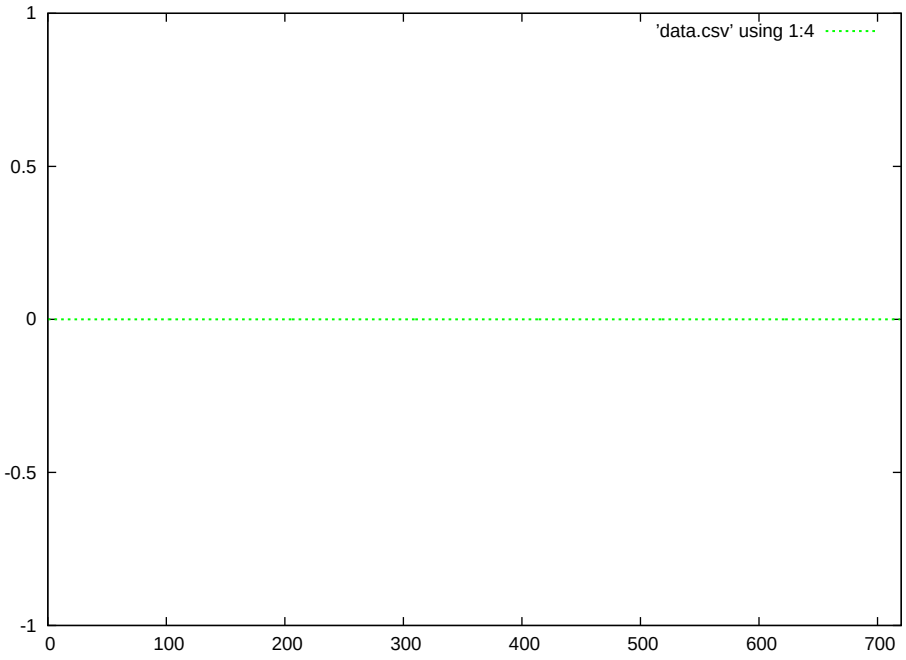


Green = superposition of the forward and reflected waves



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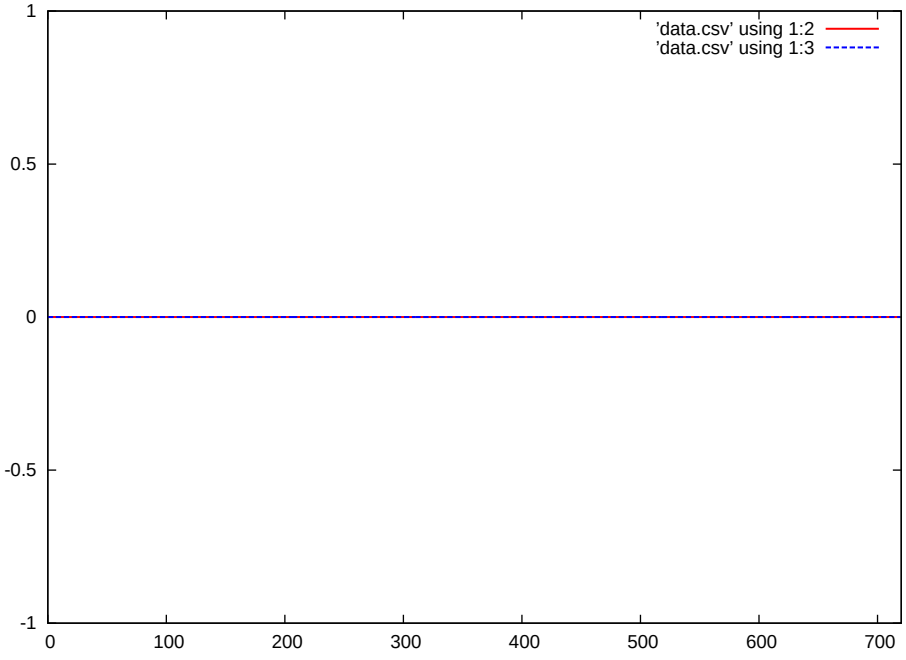

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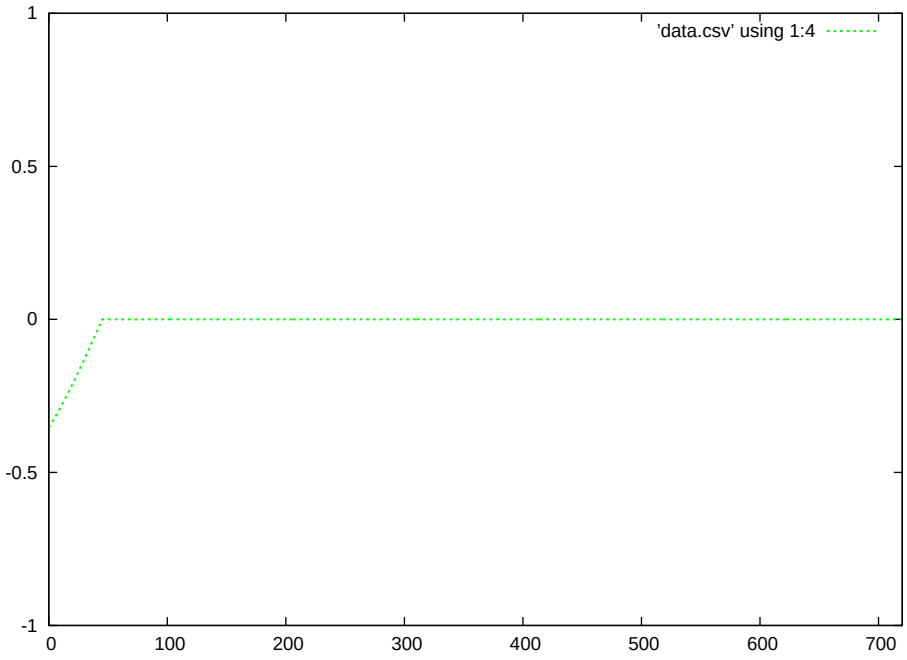

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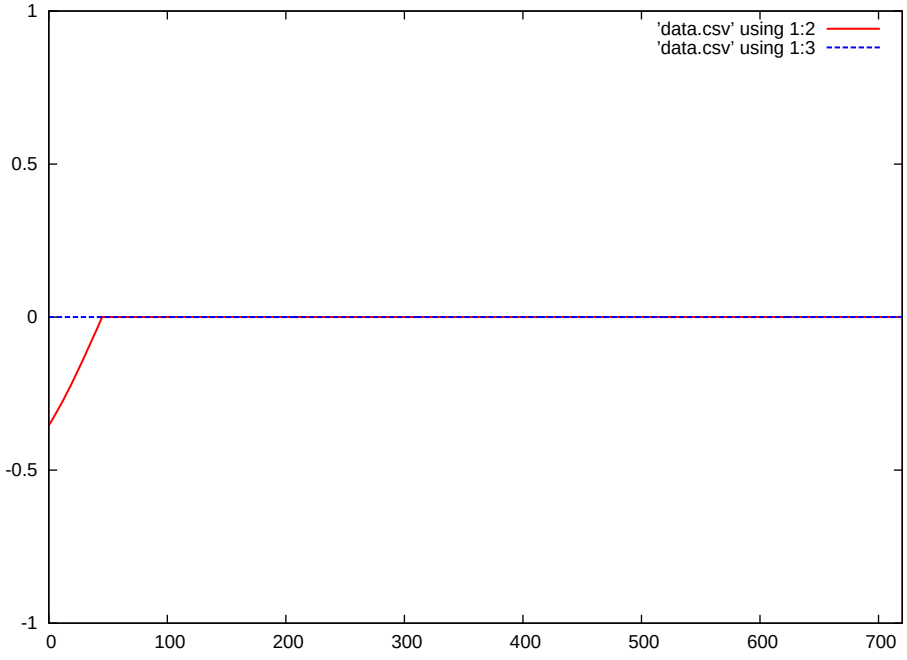

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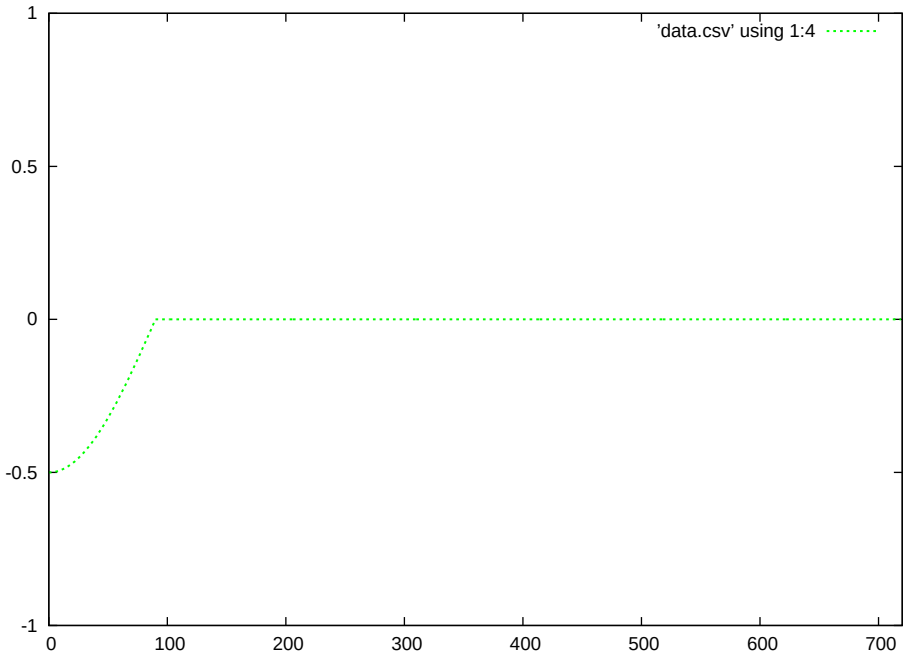

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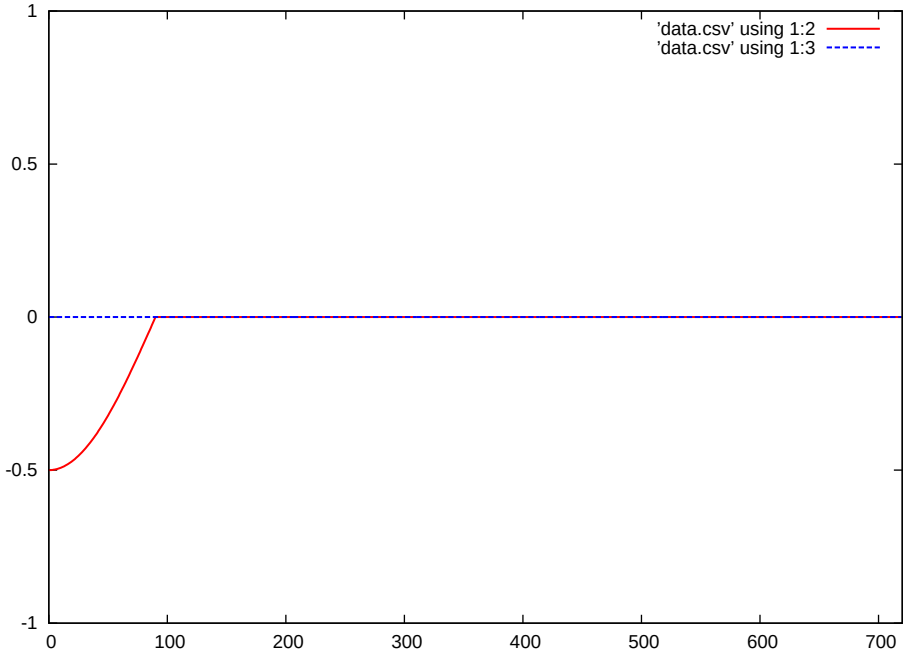

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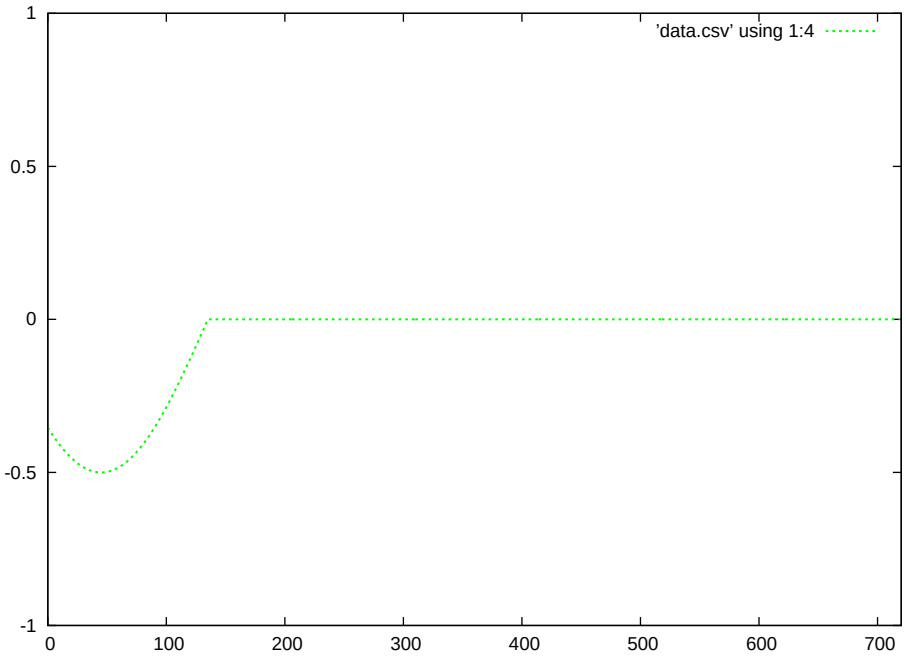

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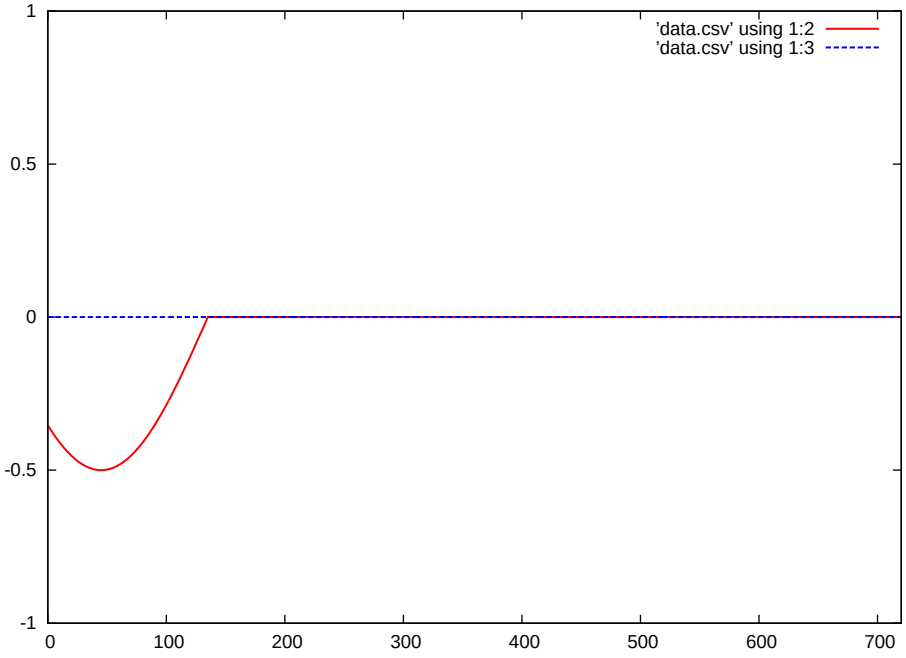

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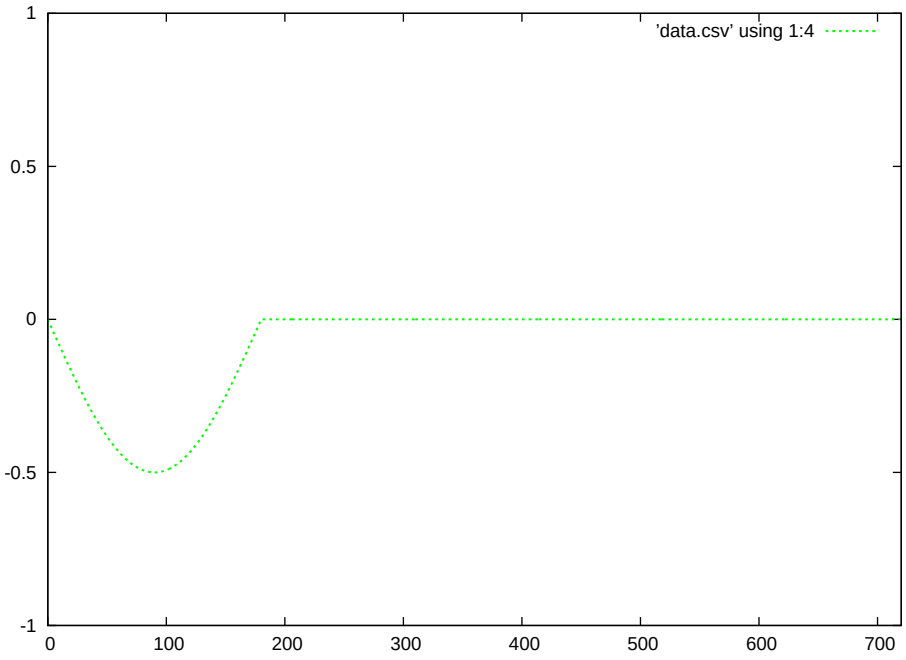

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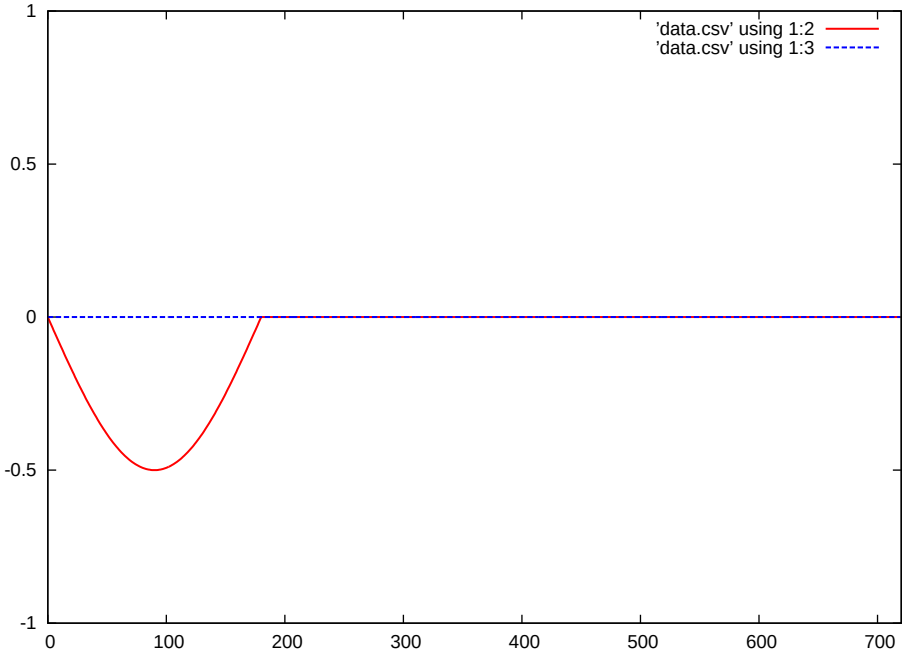

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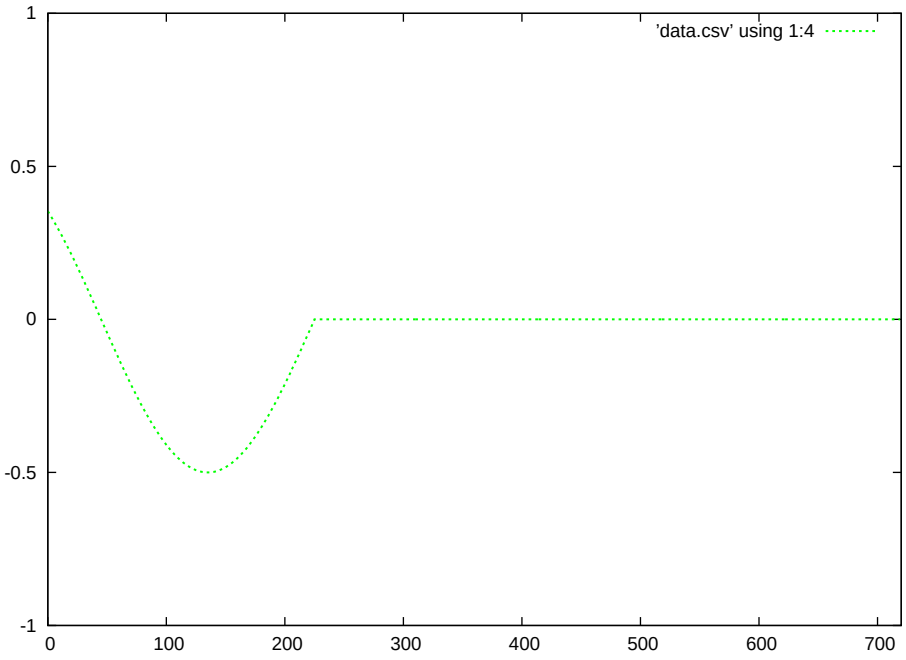

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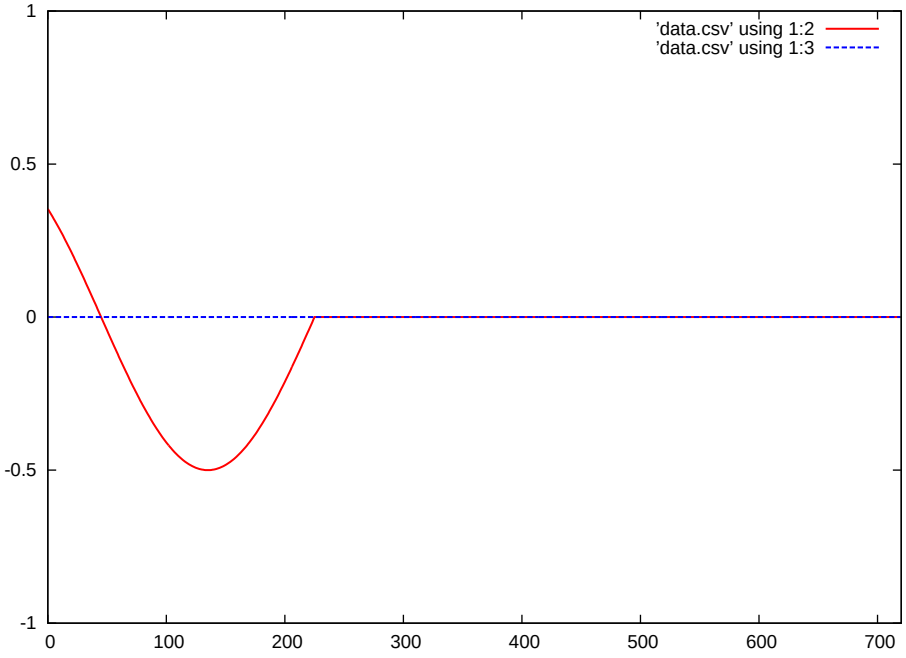

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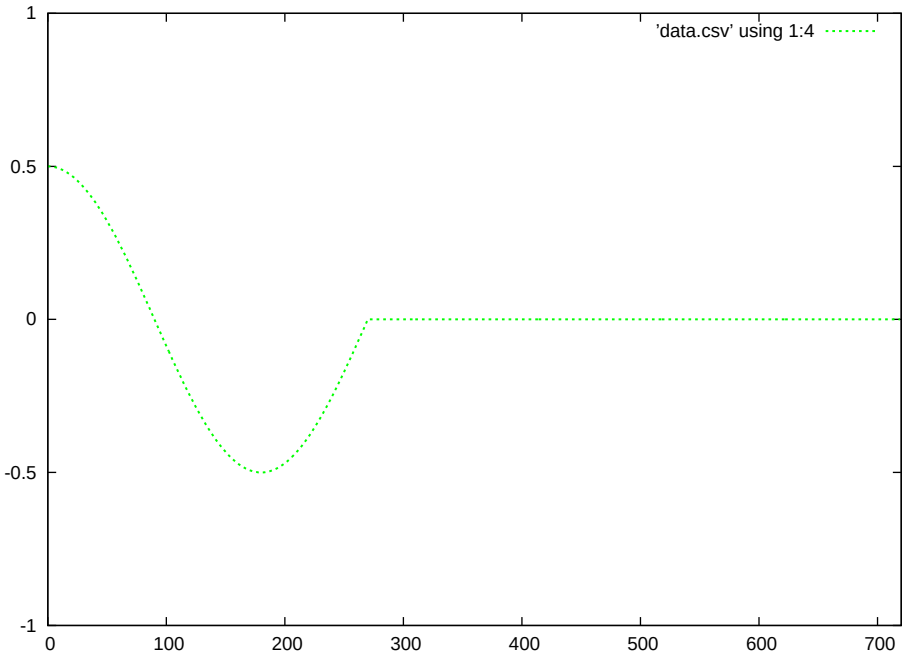

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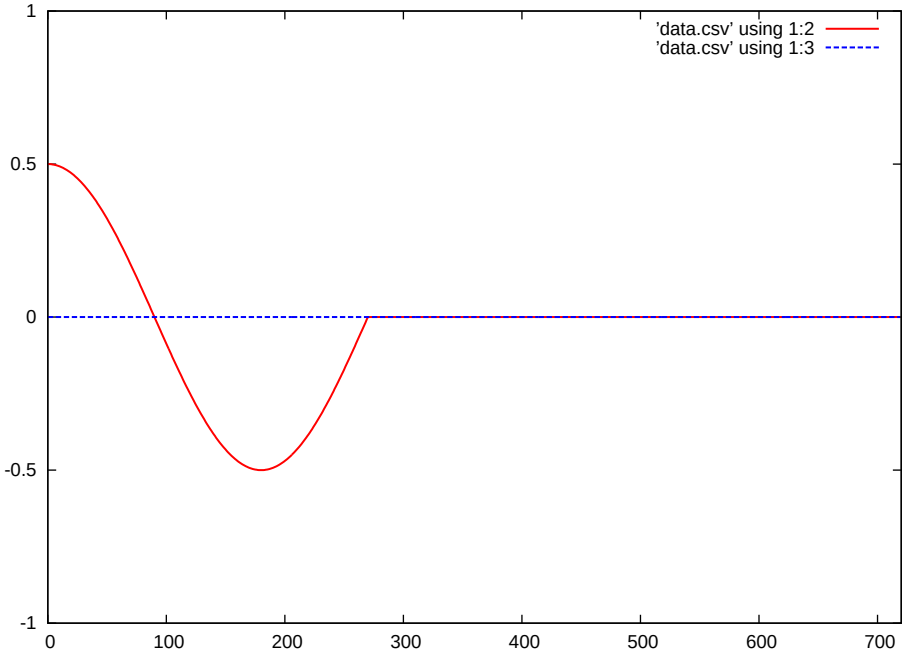

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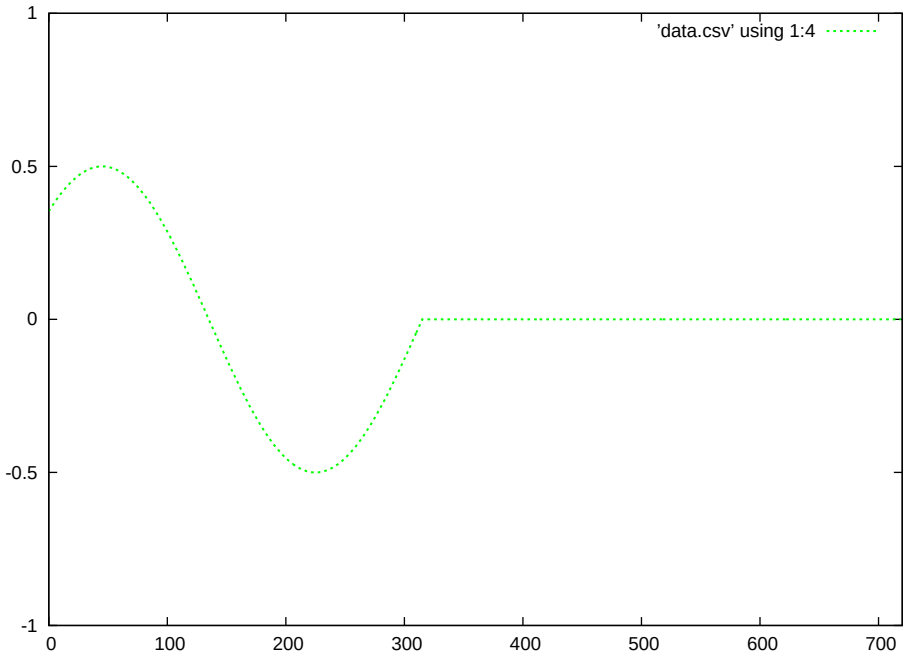

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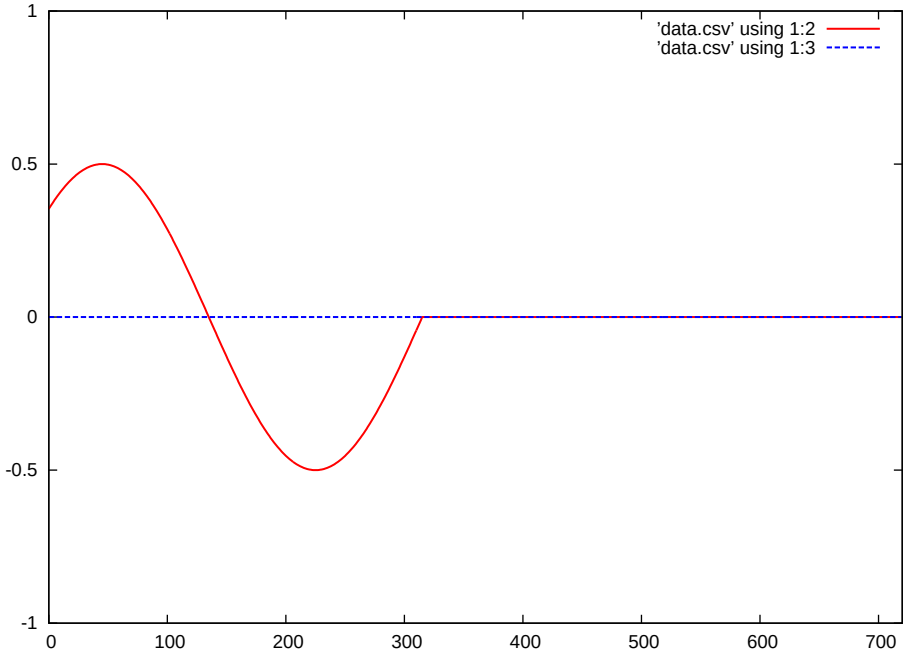

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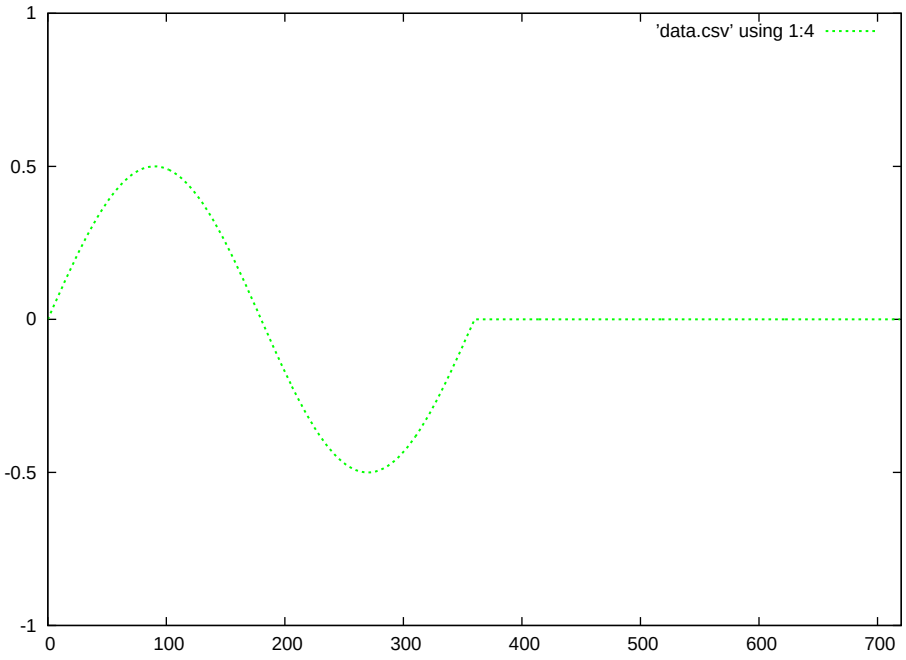

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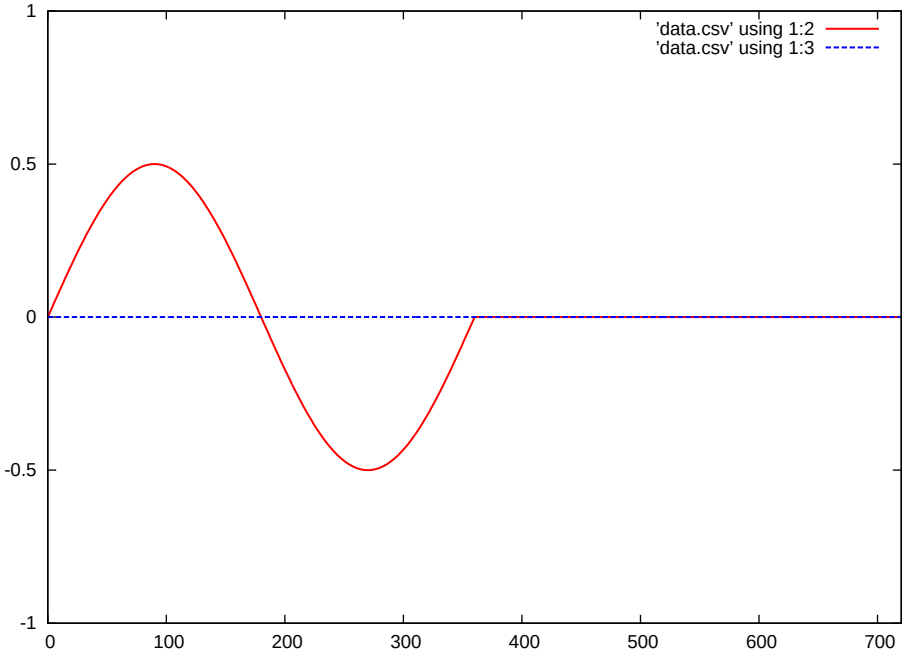

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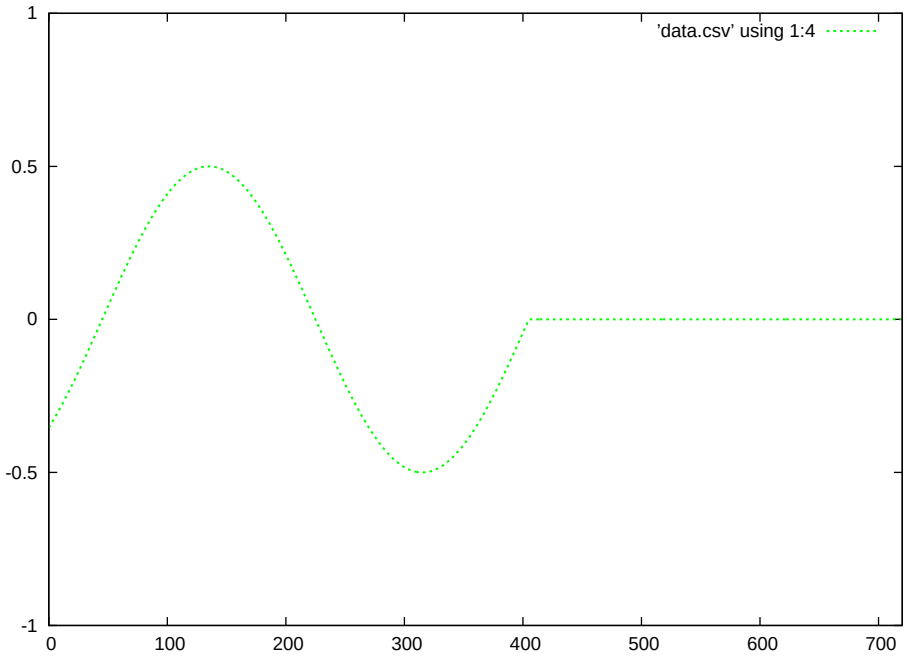

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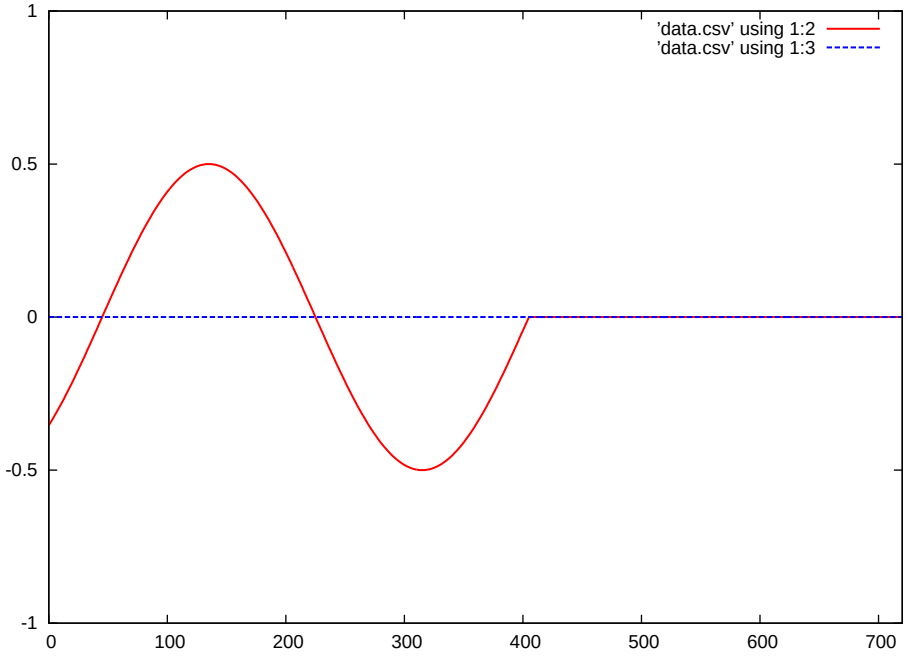

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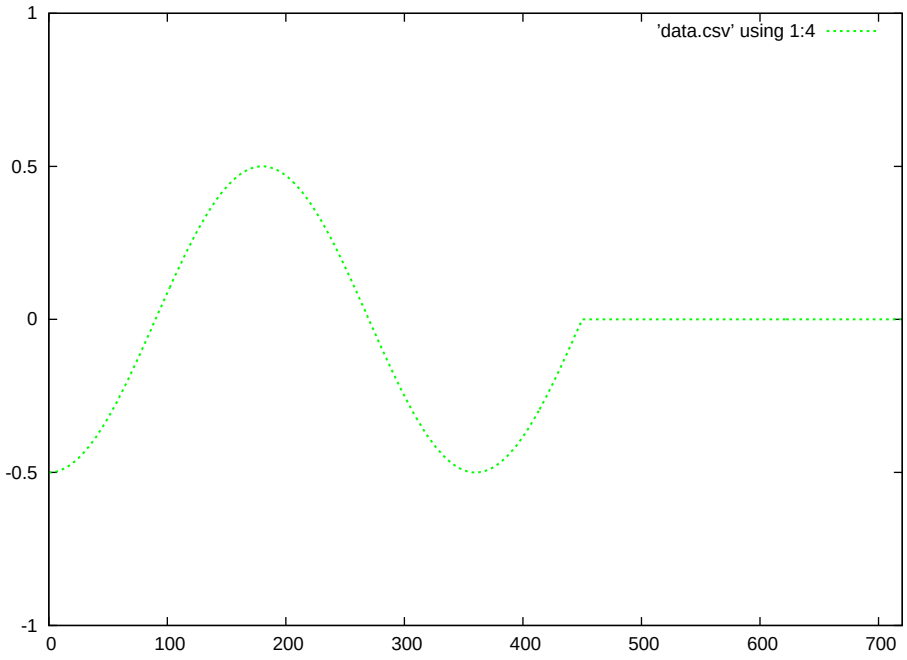

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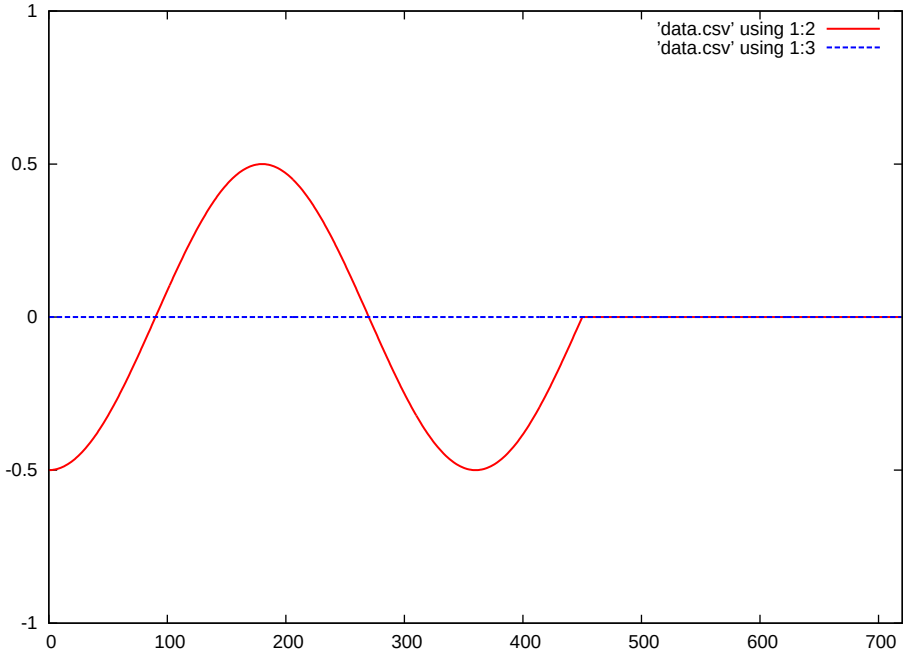

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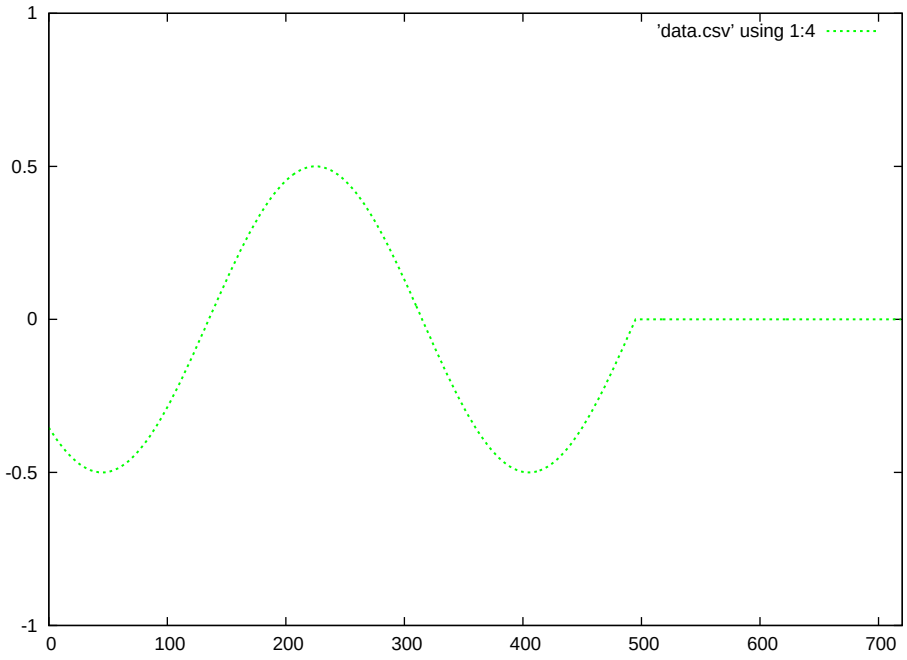

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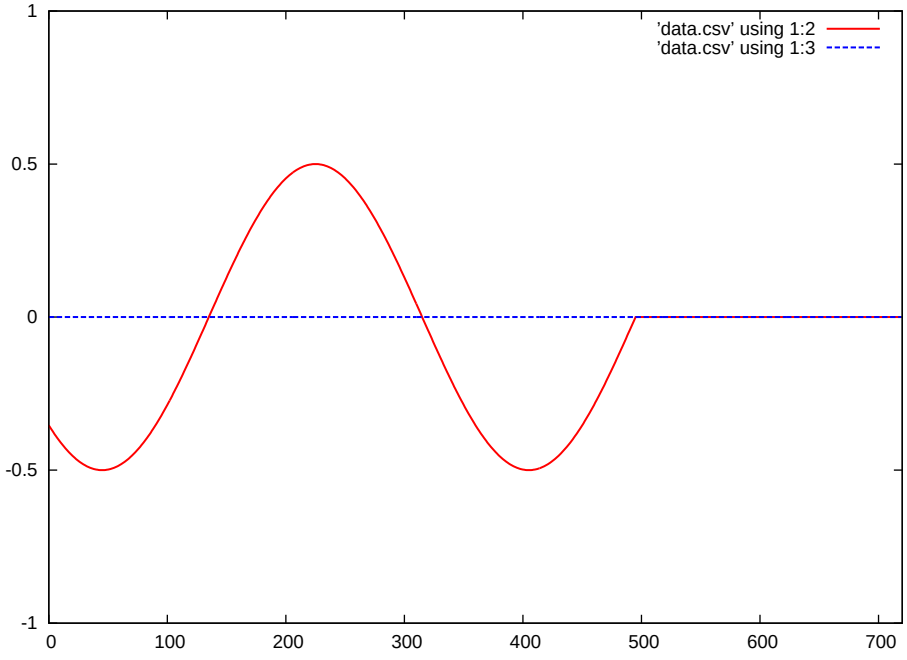

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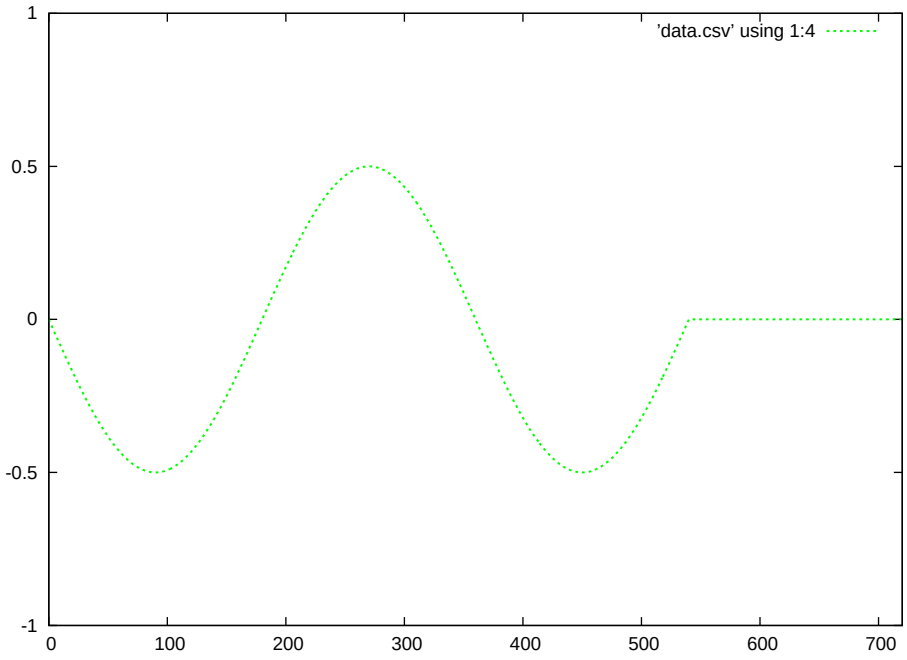

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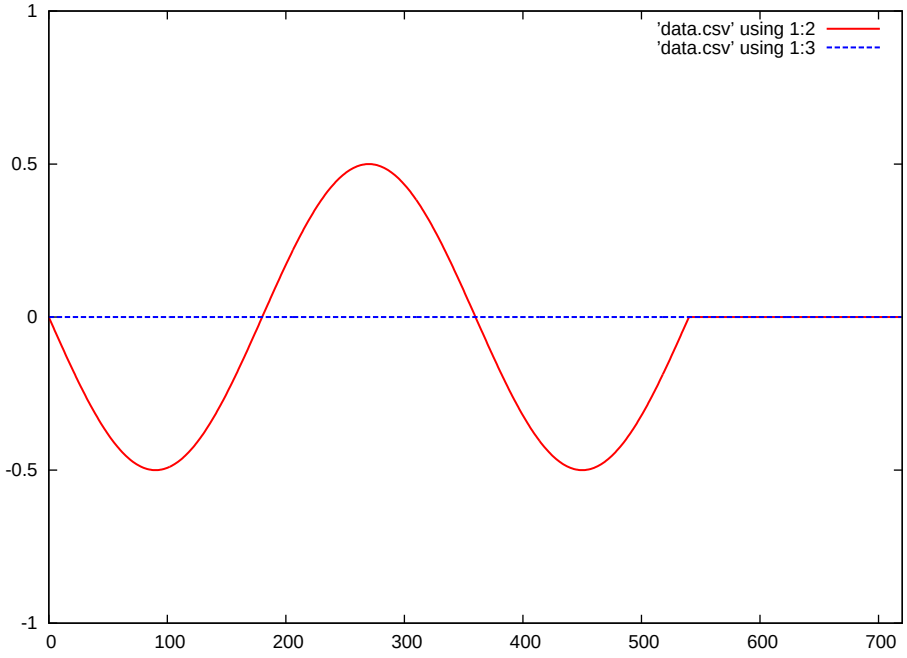

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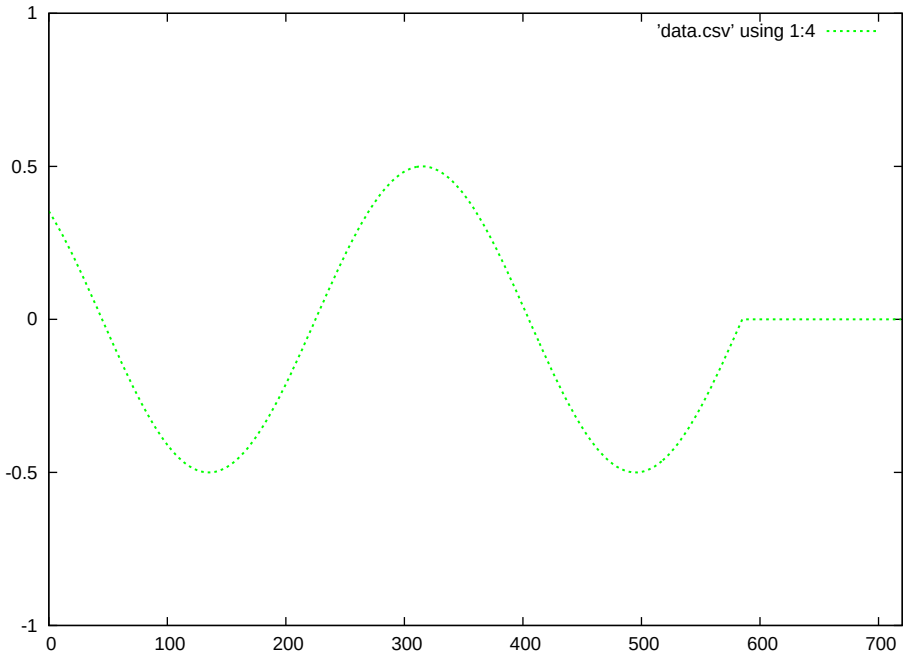

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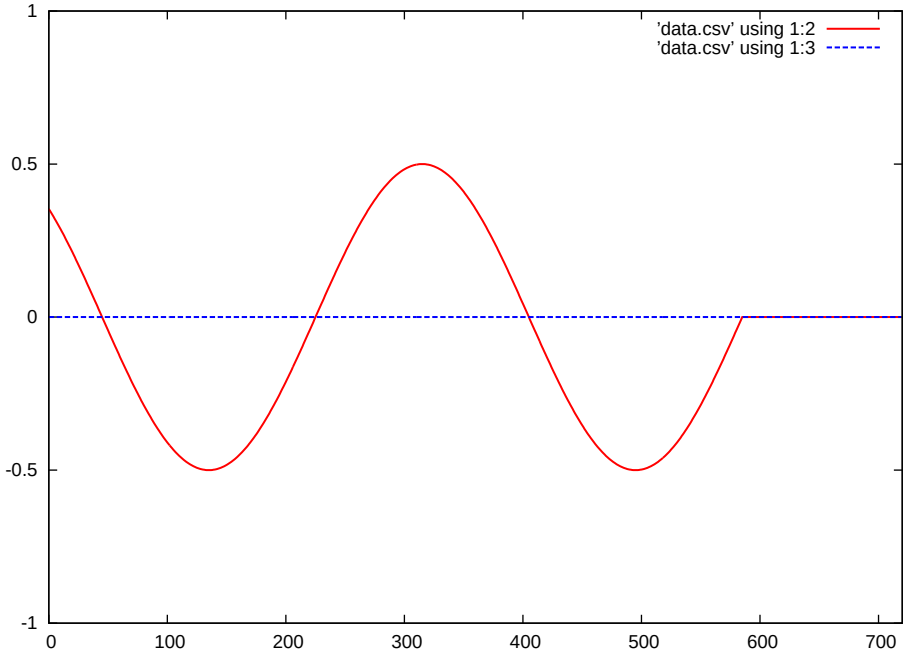

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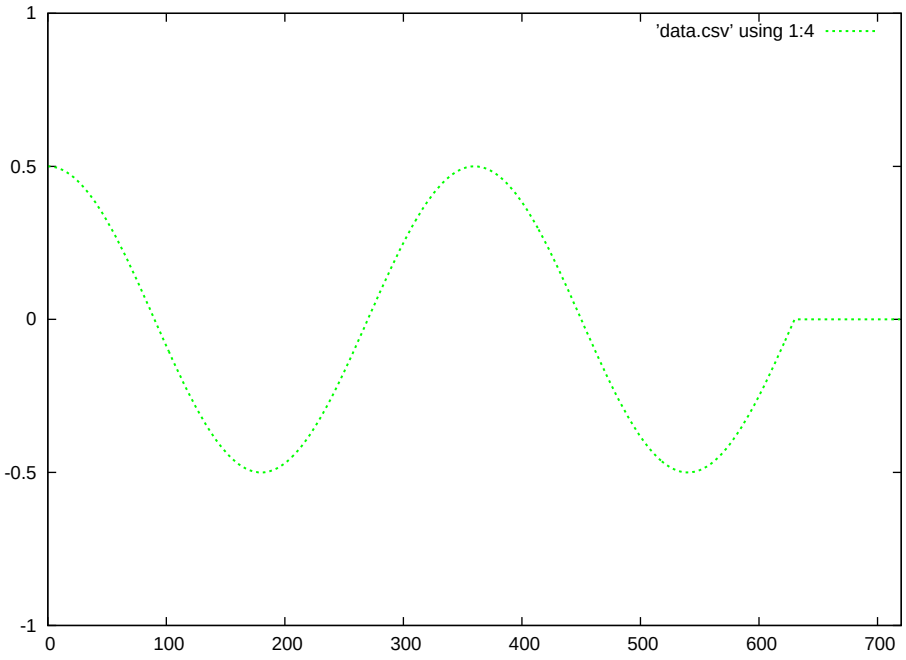

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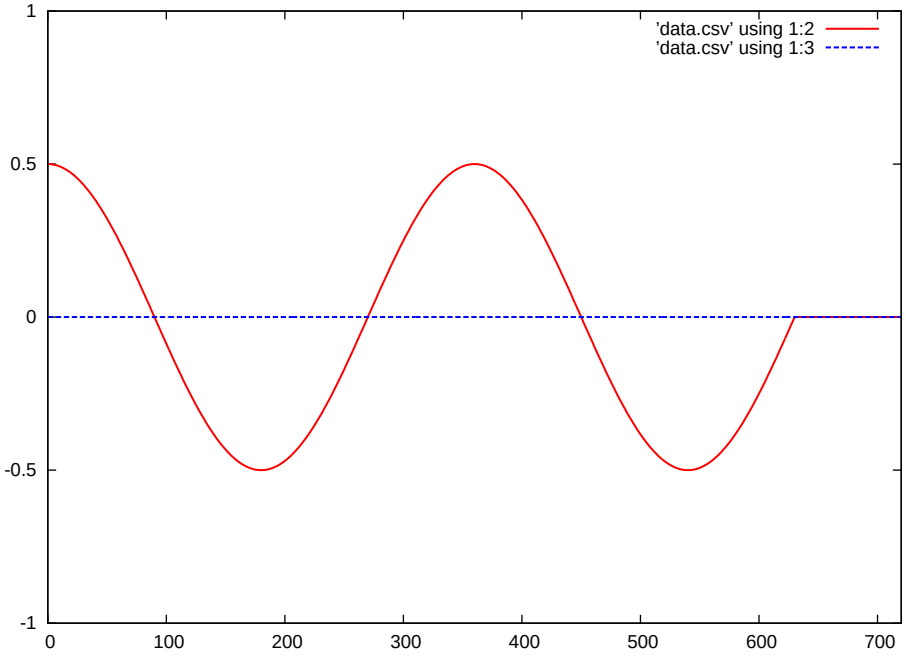

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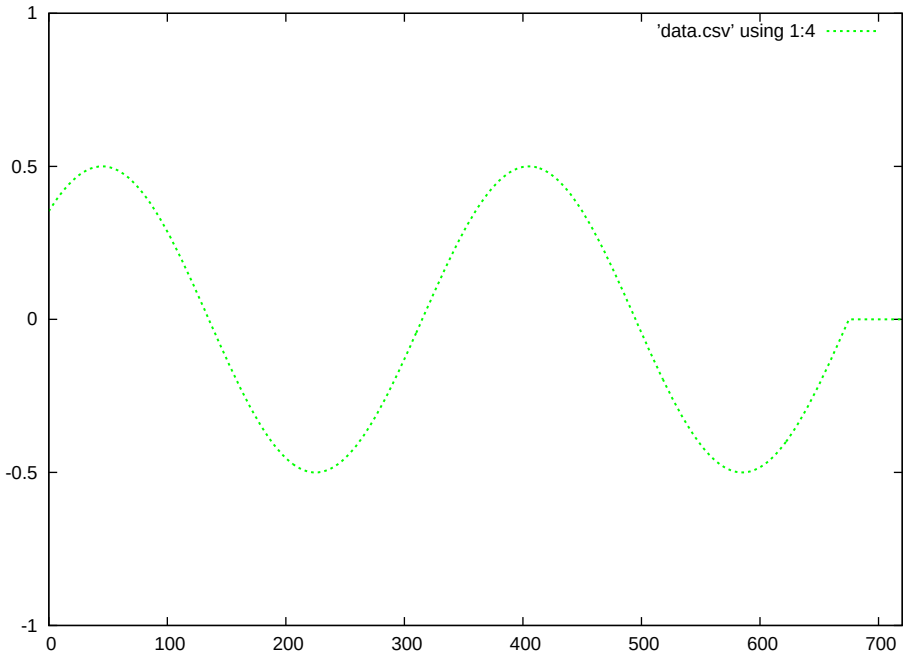

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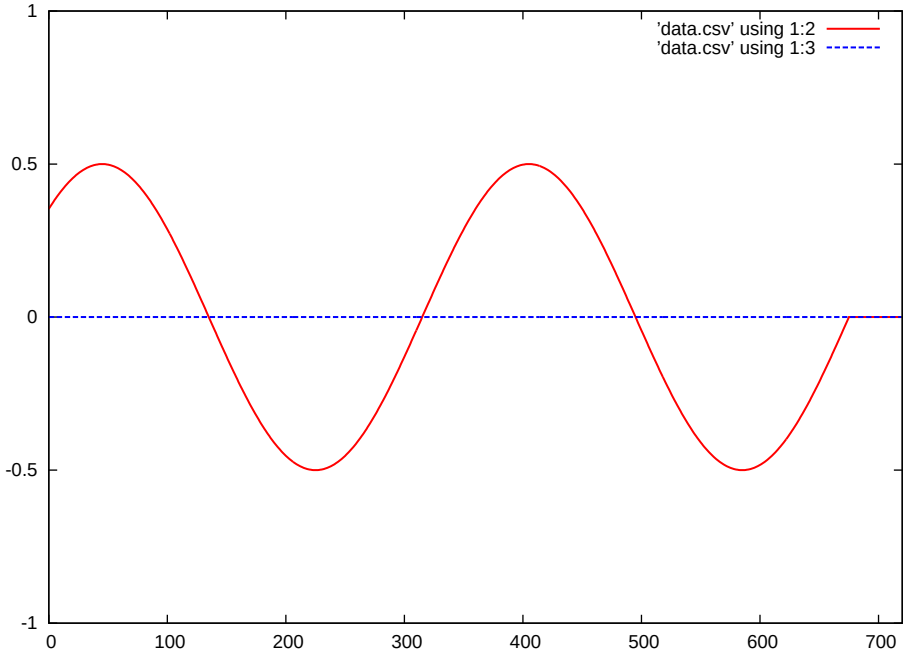

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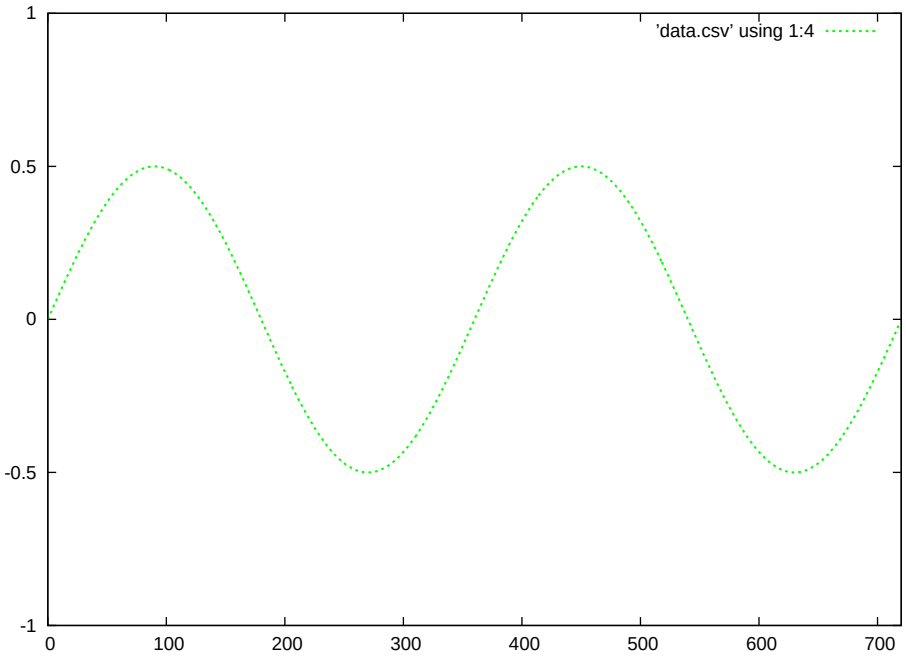

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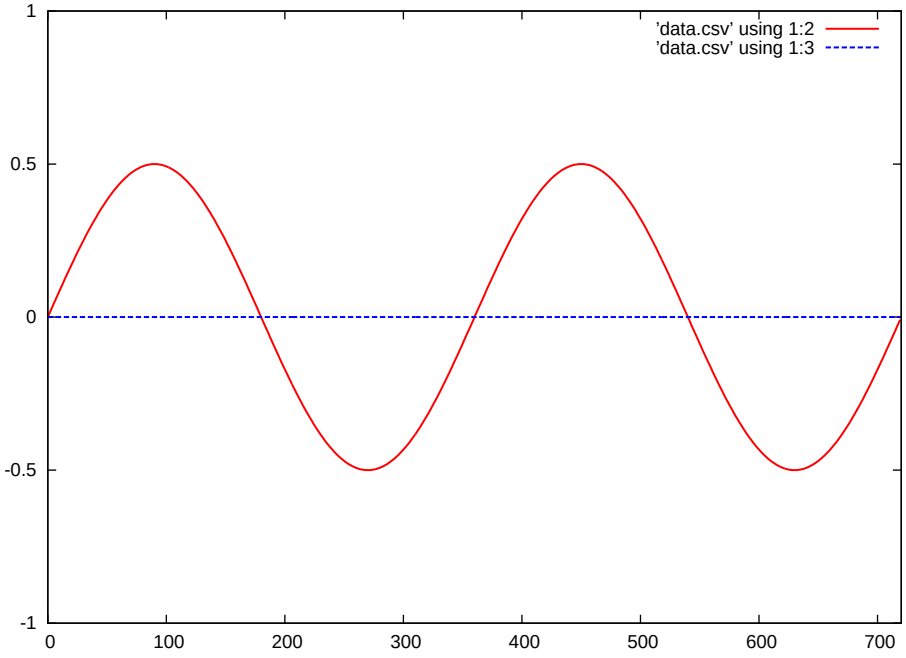

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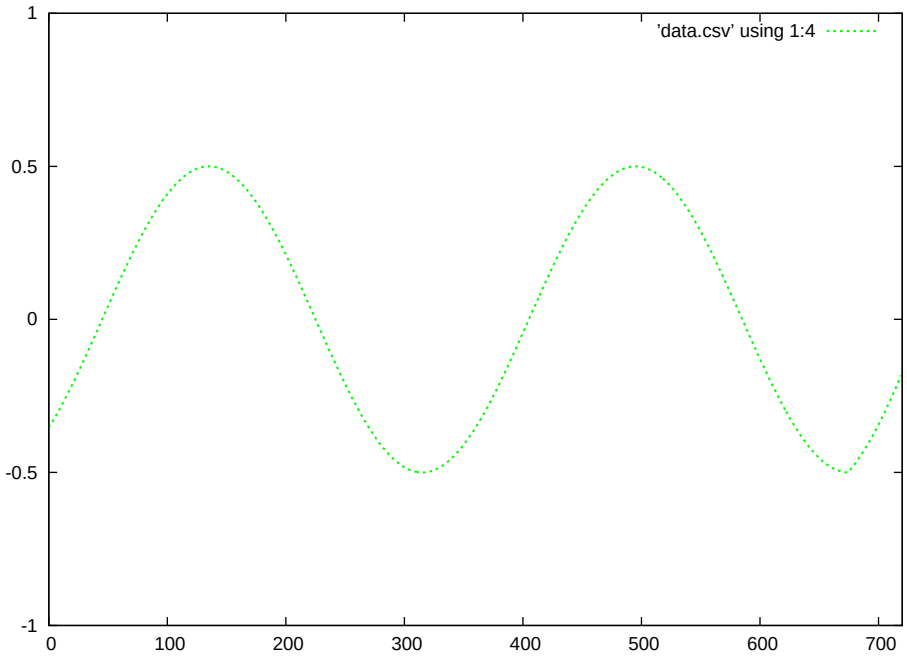

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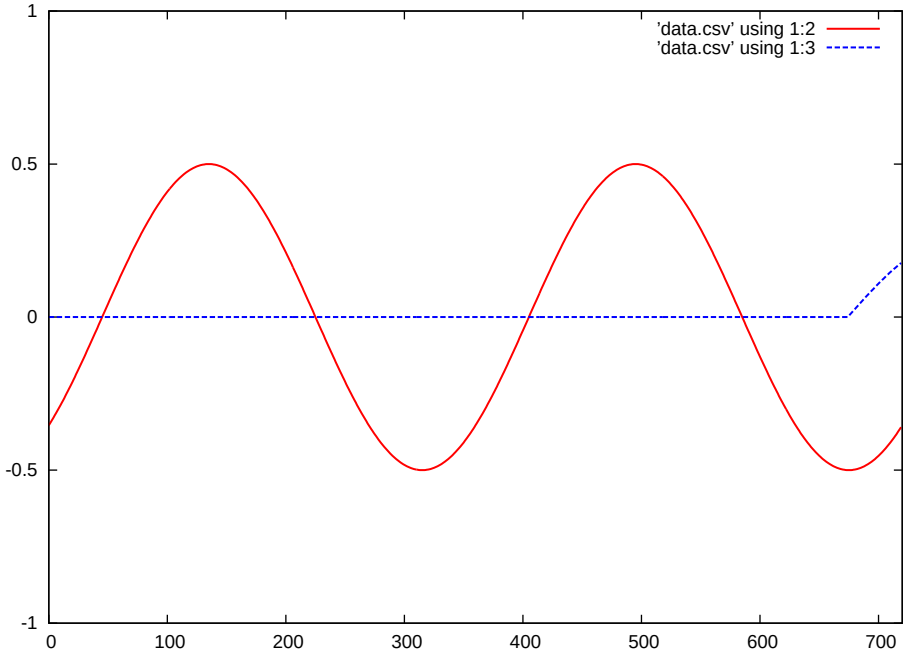

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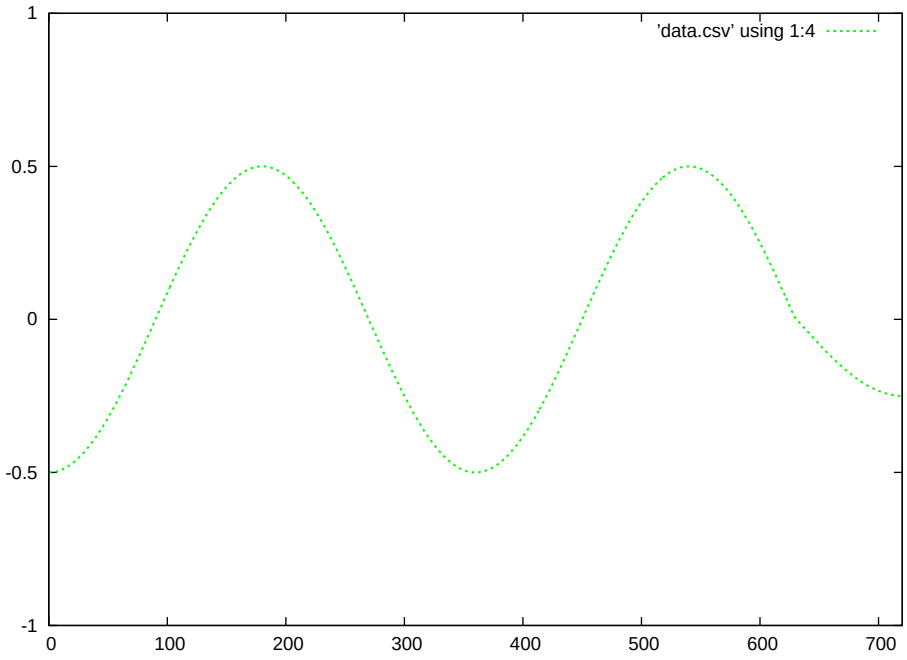

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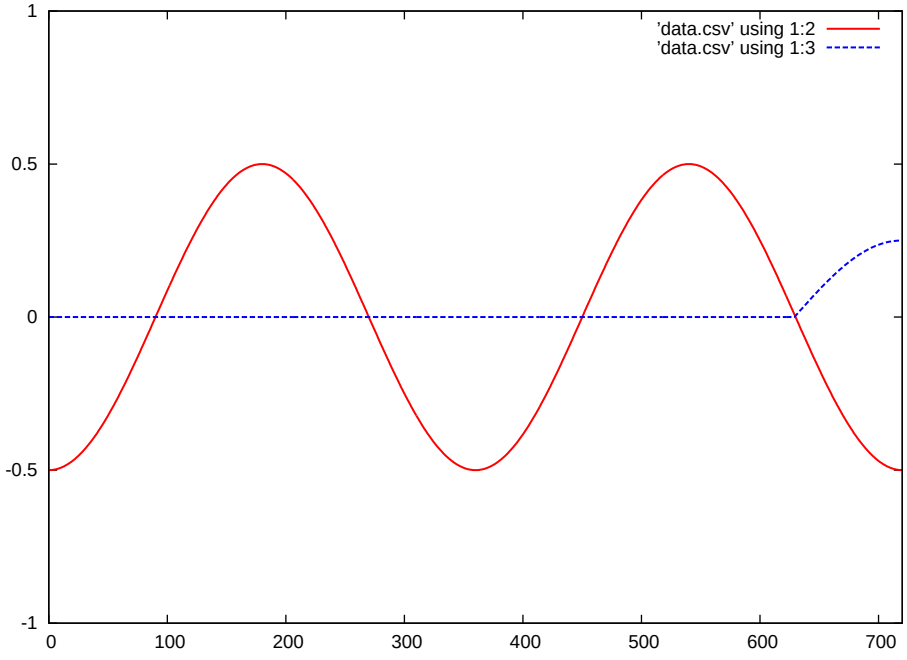

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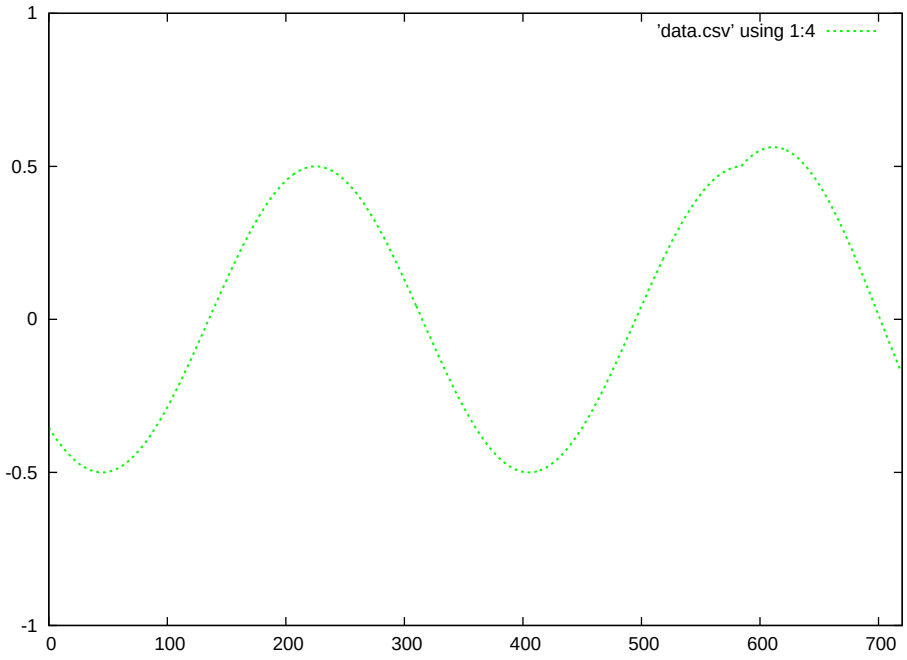

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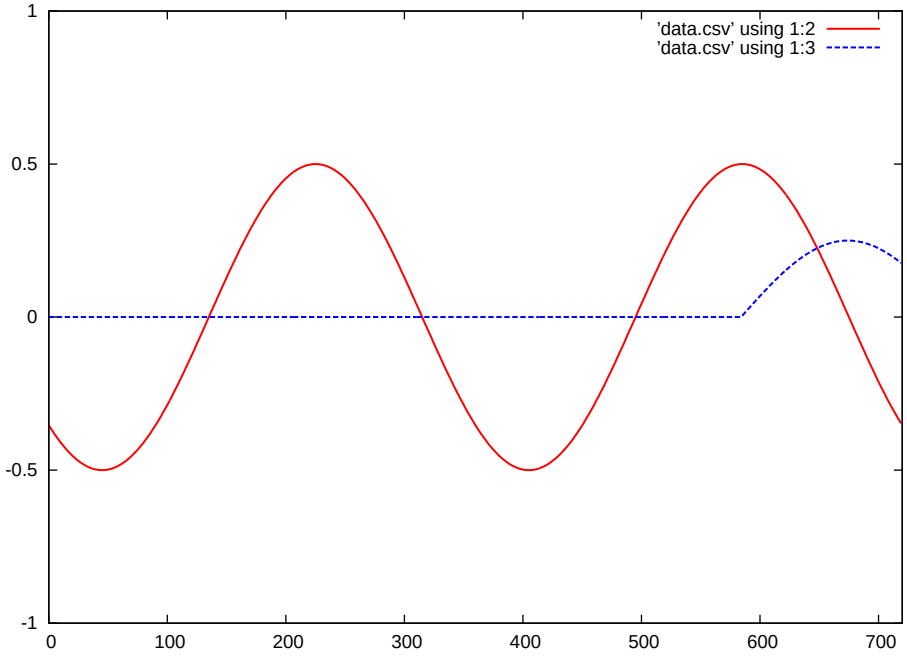

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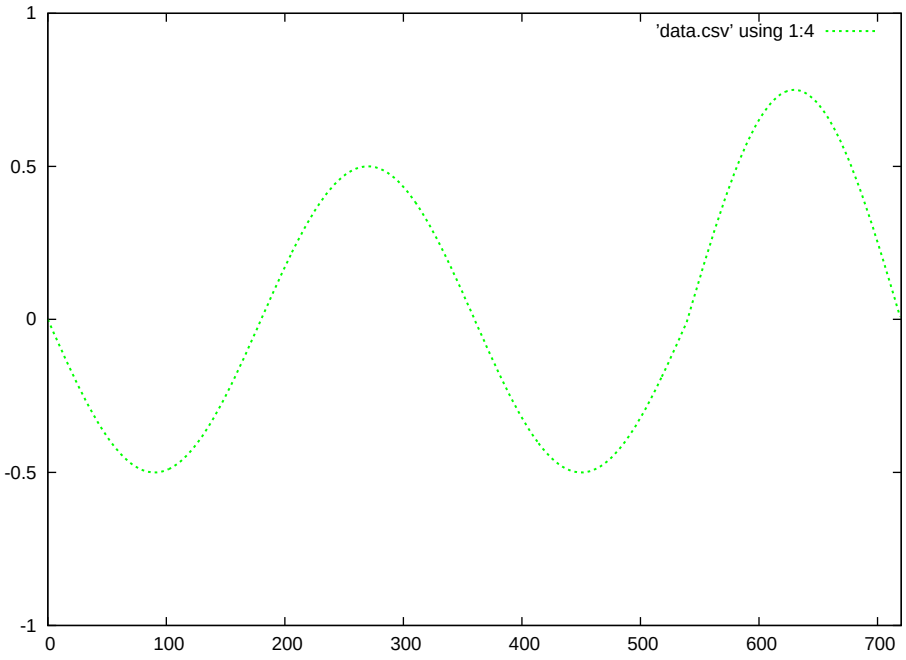
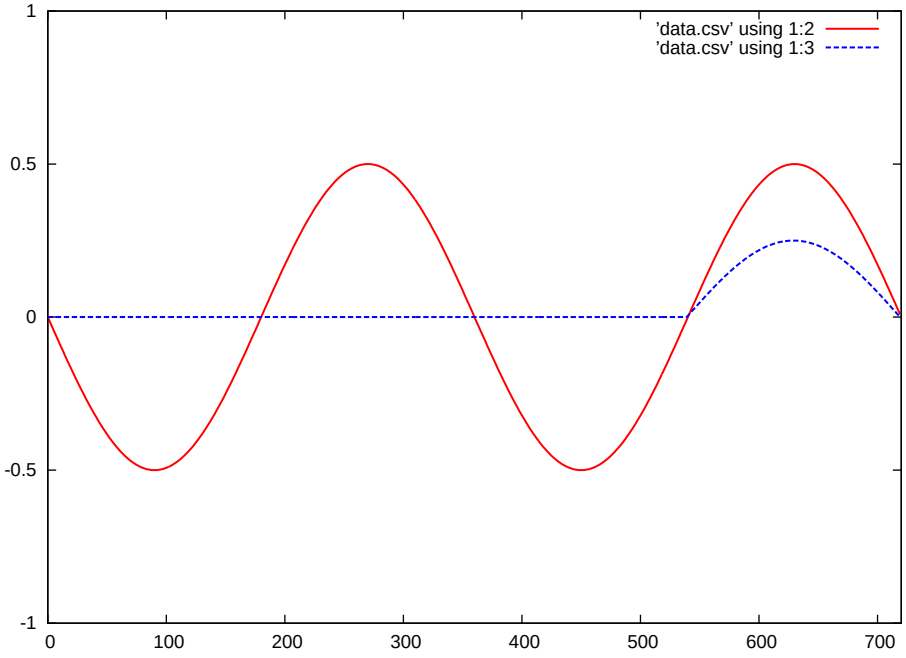
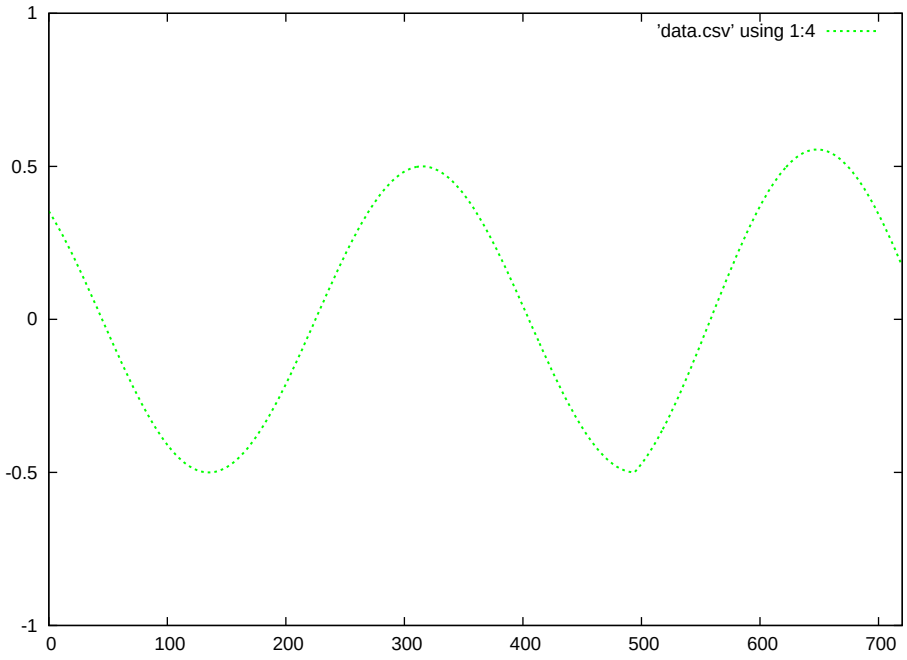


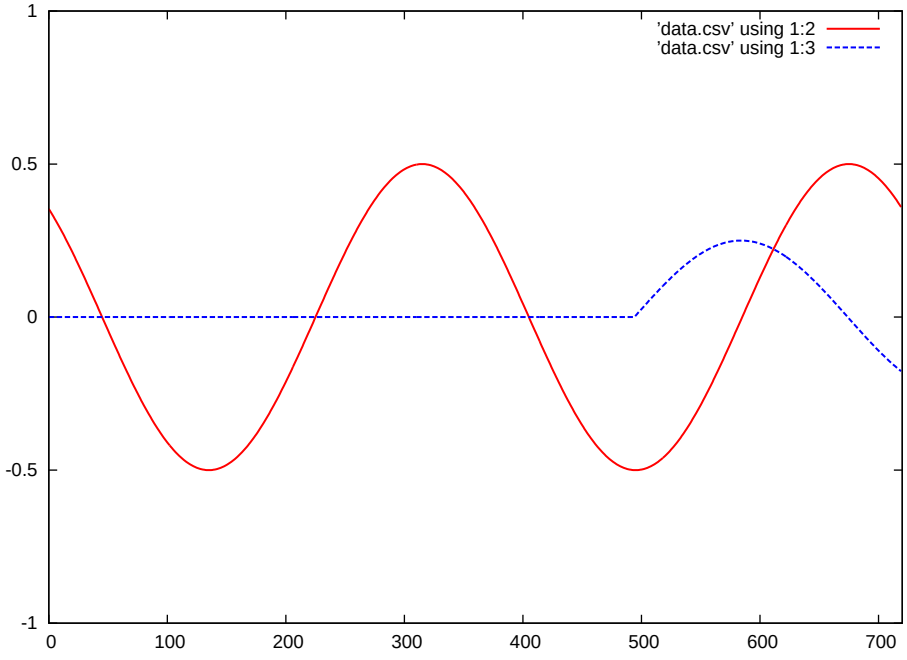
Red = forward wave Blue = reflected wave



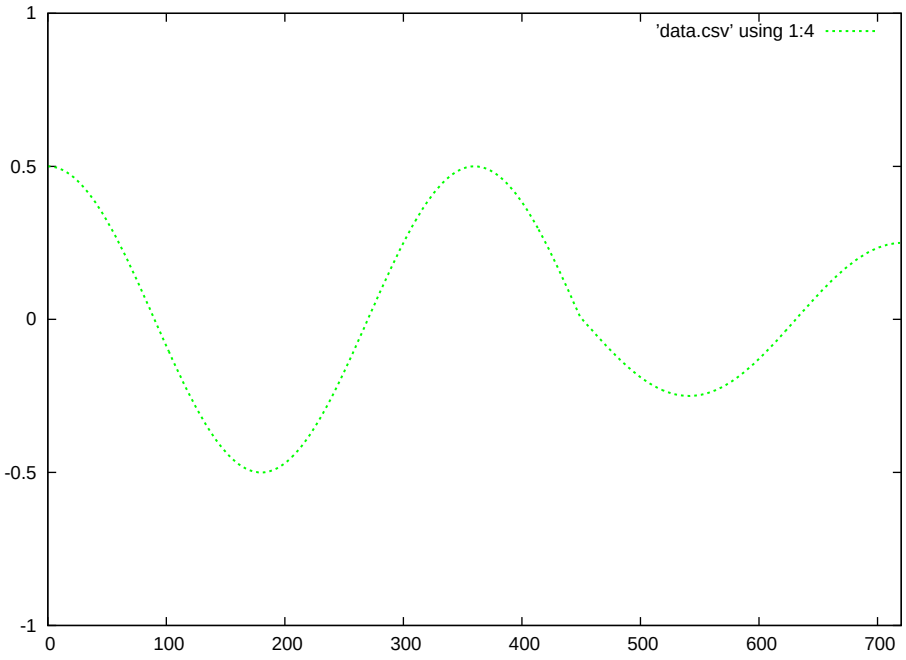
Green = superposition of the forward and reflected waves



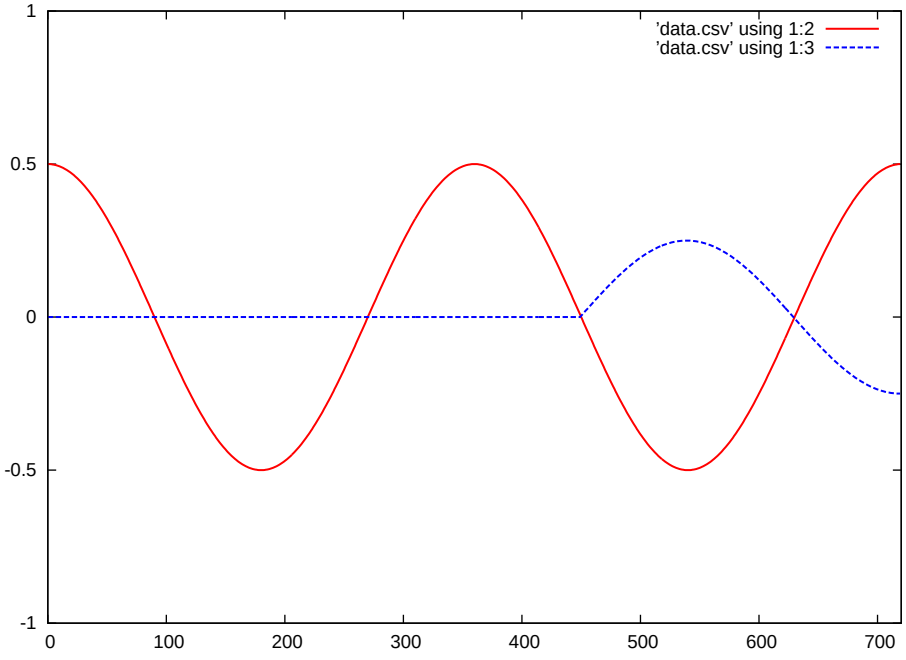
Red = forward wave Blue = reflected wave



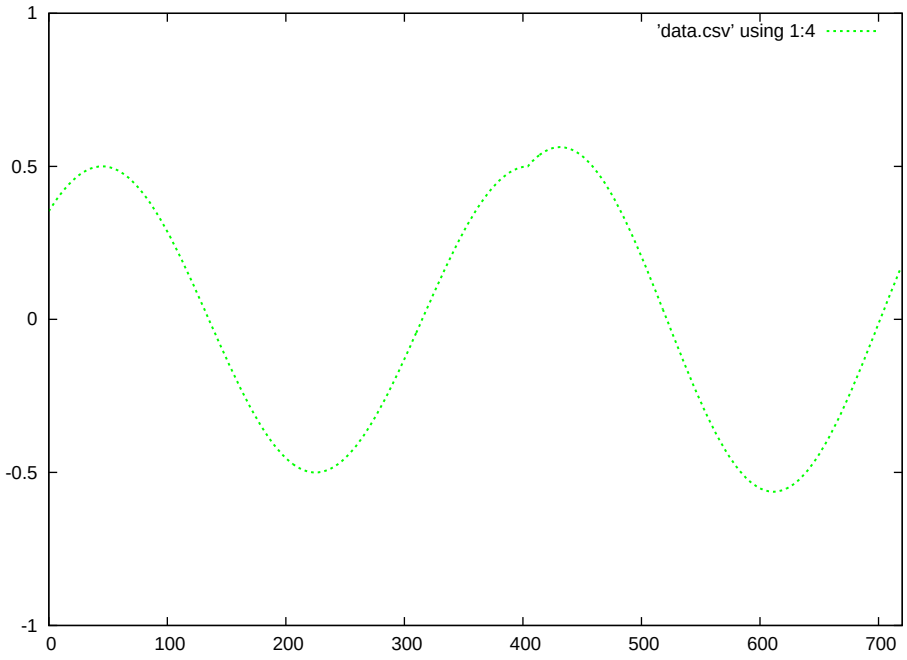
Green = superposition of the forward and reflected waves



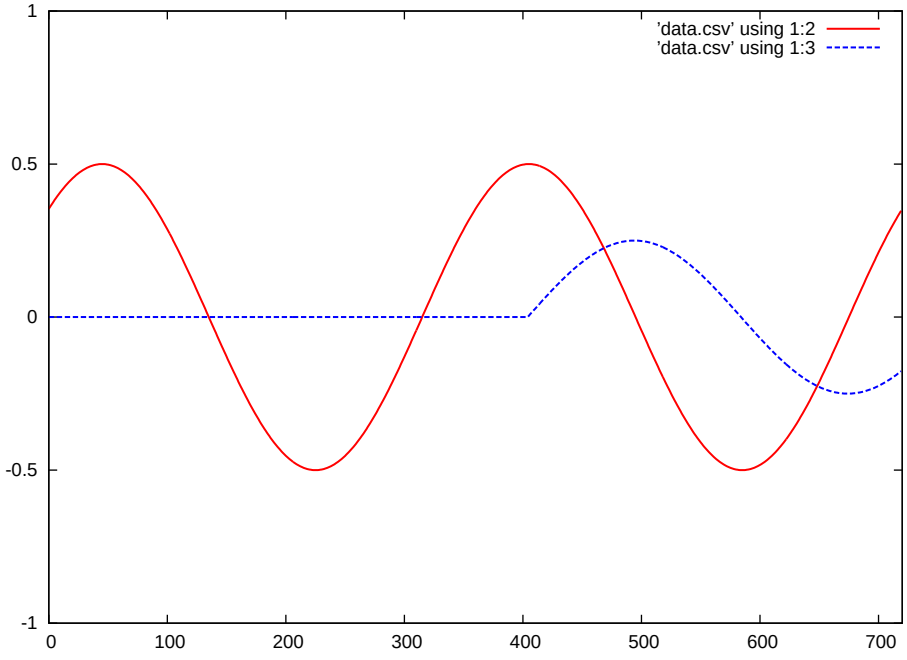
Red = forward wave Blue = reflected wave



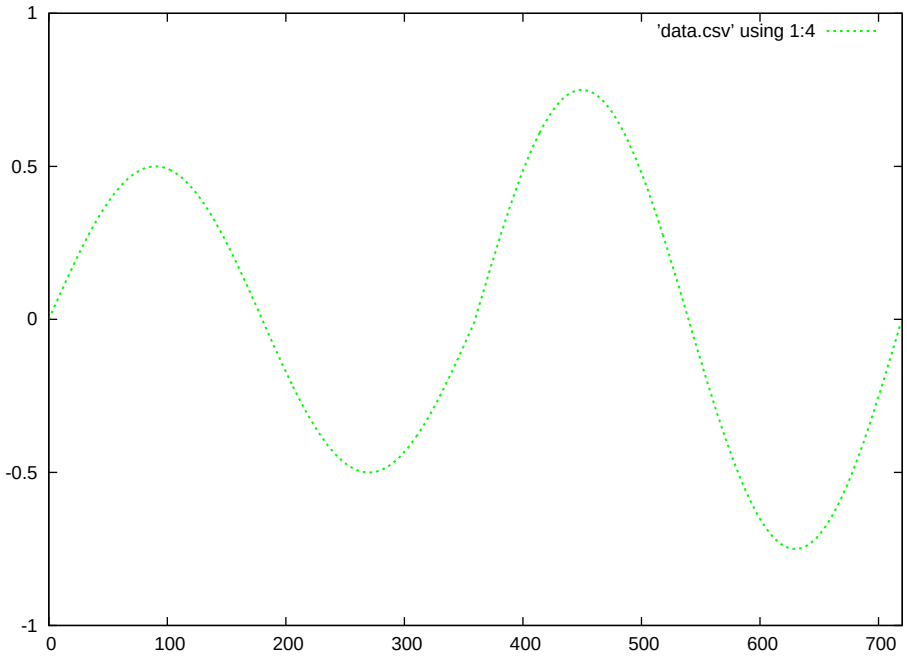
Green = superposition of the forward and reflected waves



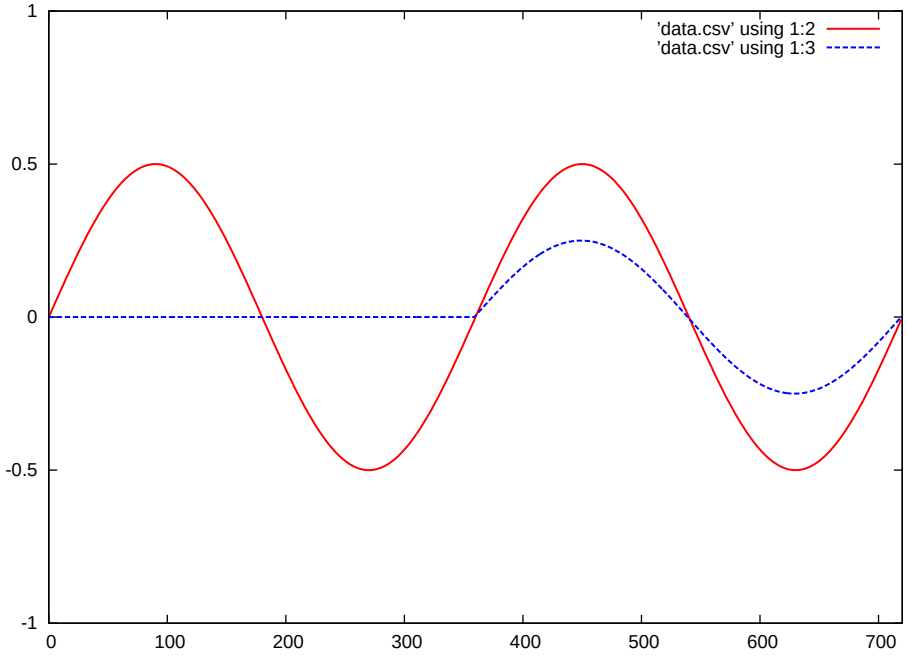
Red = forward wave Blue = reflected wave



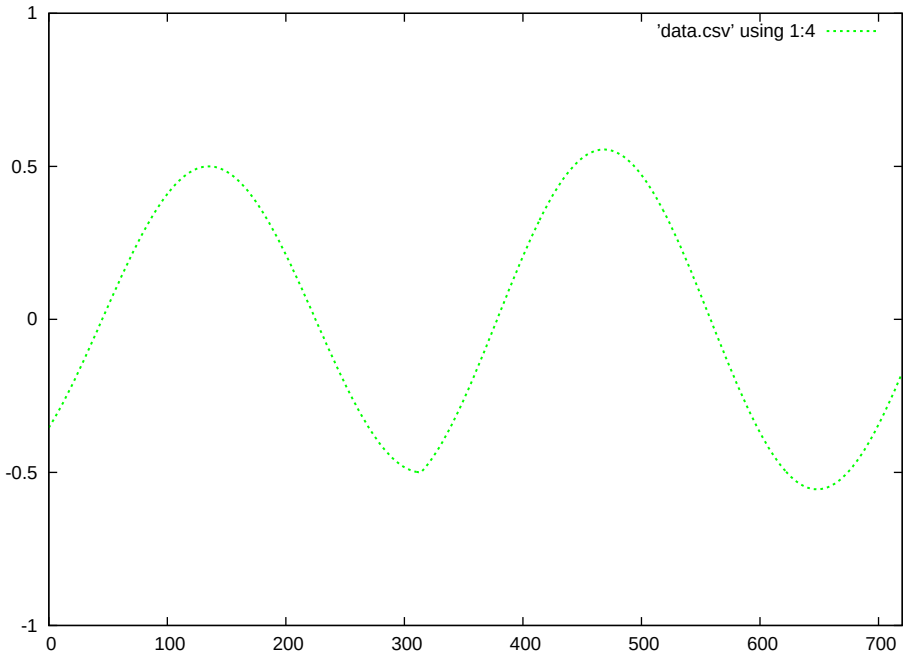
Green = superposition of the forward and reflected waves



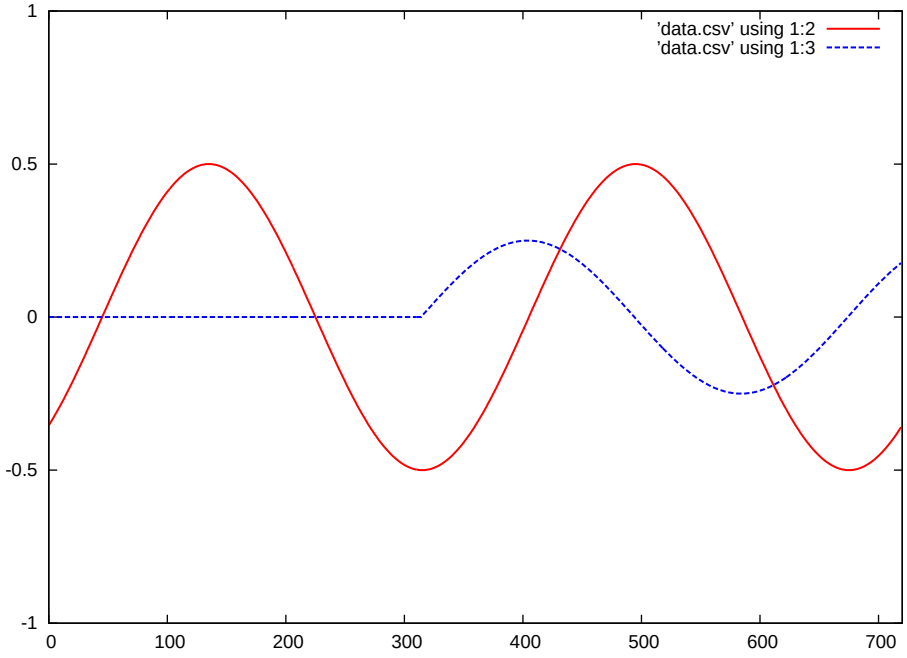
Red = forward wave Blue = reflected wave



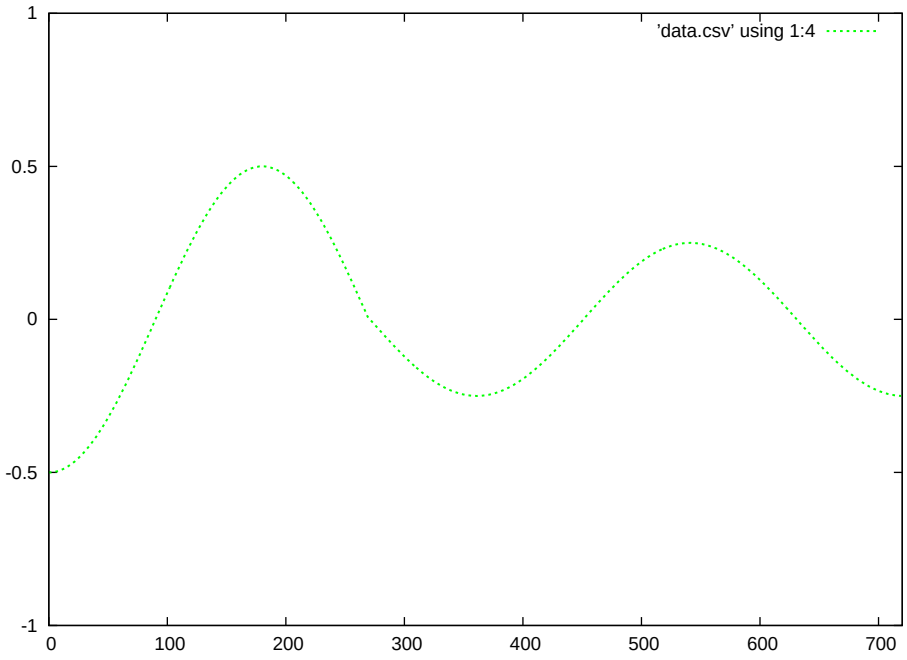
Green = superposition of the forward and reflected waves



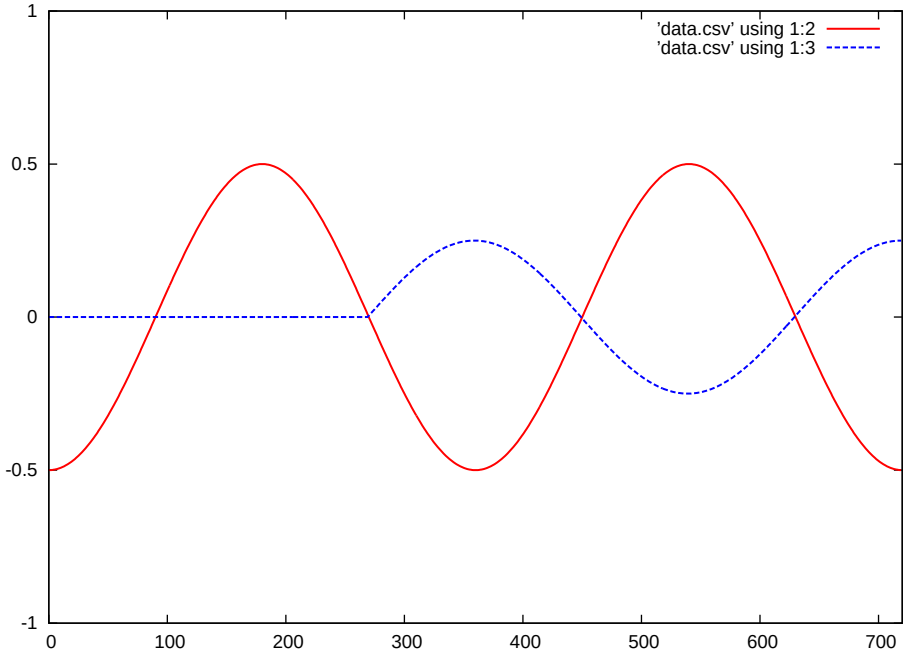
Red = forward wave Blue = reflected wave



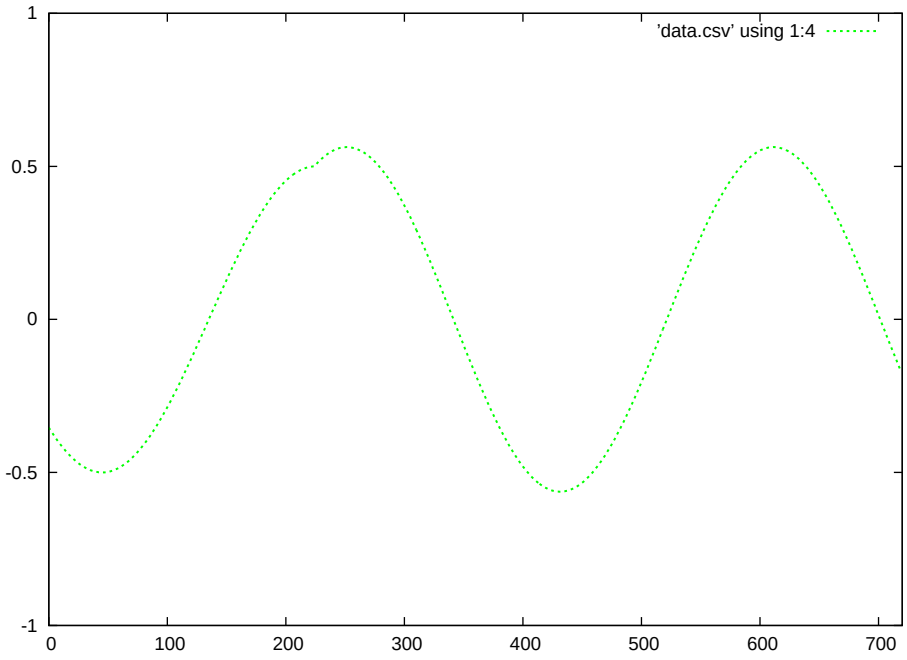
Green = superposition of the forward and reflected waves



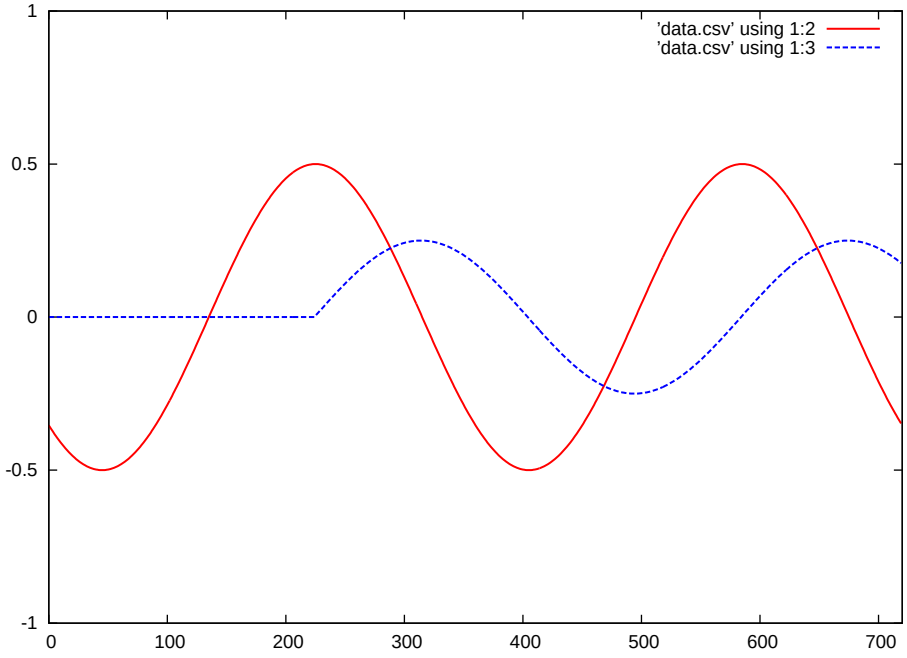
Red = forward wave Blue = reflected wave



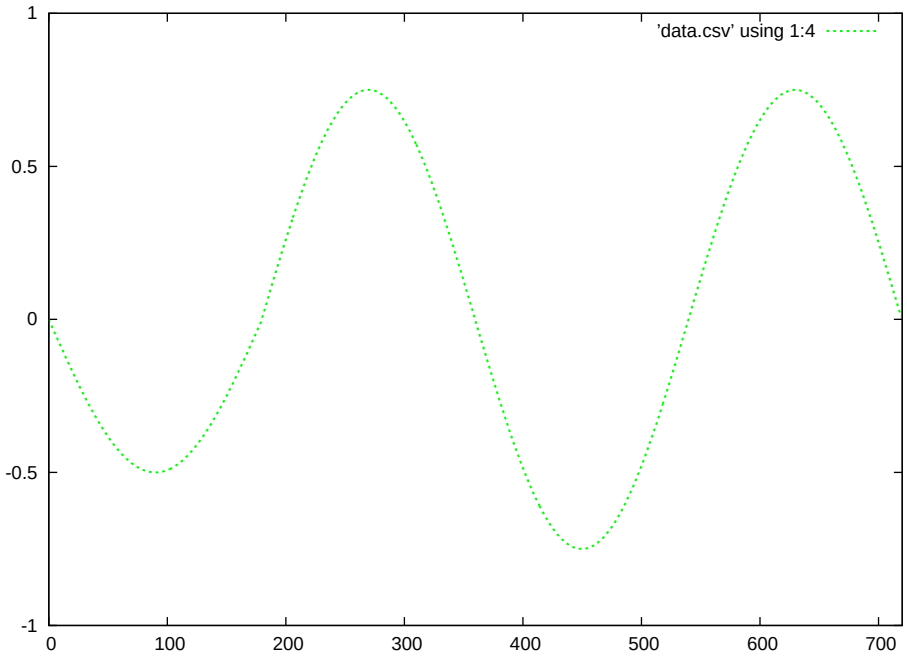
Green = superposition of the forward and reflected waves



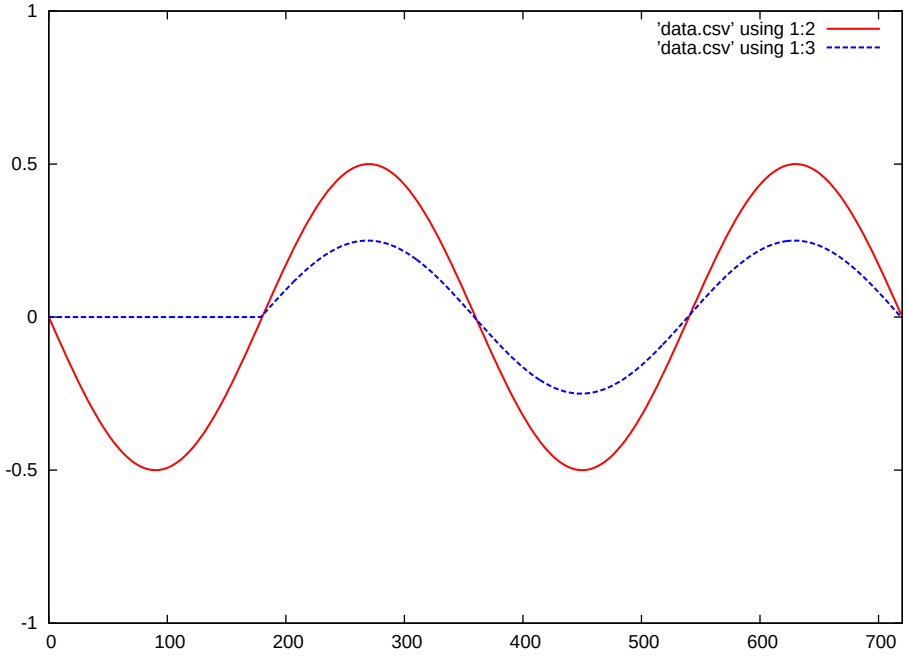
Red = forward wave Blue = reflected wave



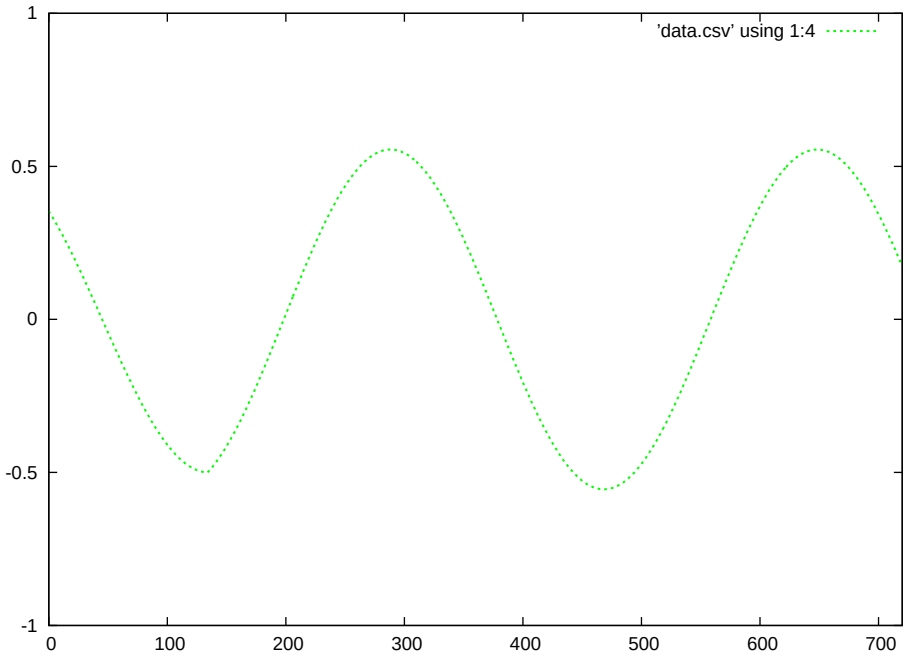
Green = superposition of the forward and reflected waves



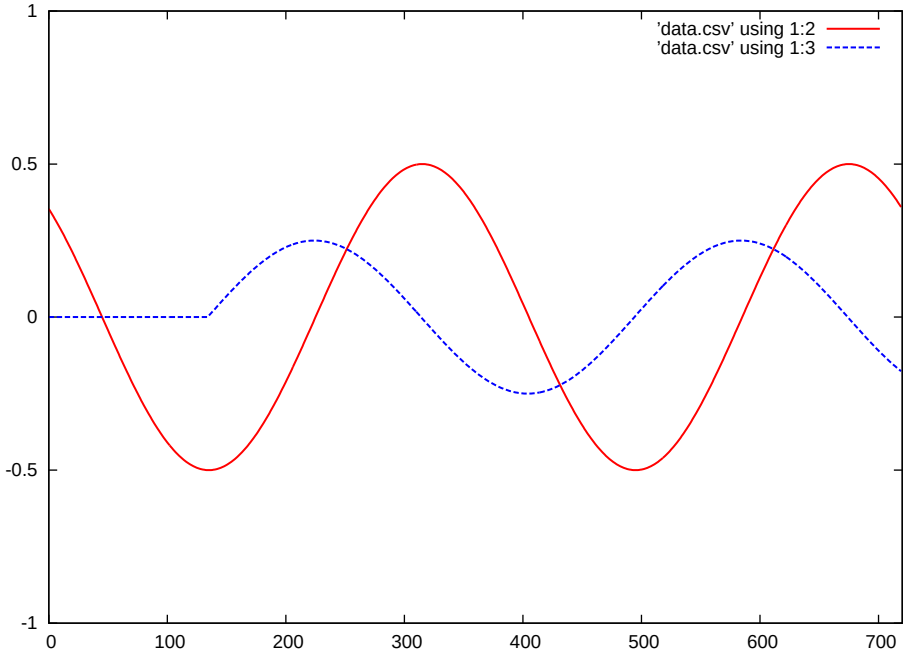
Red = forward wave Blue = reflected wave



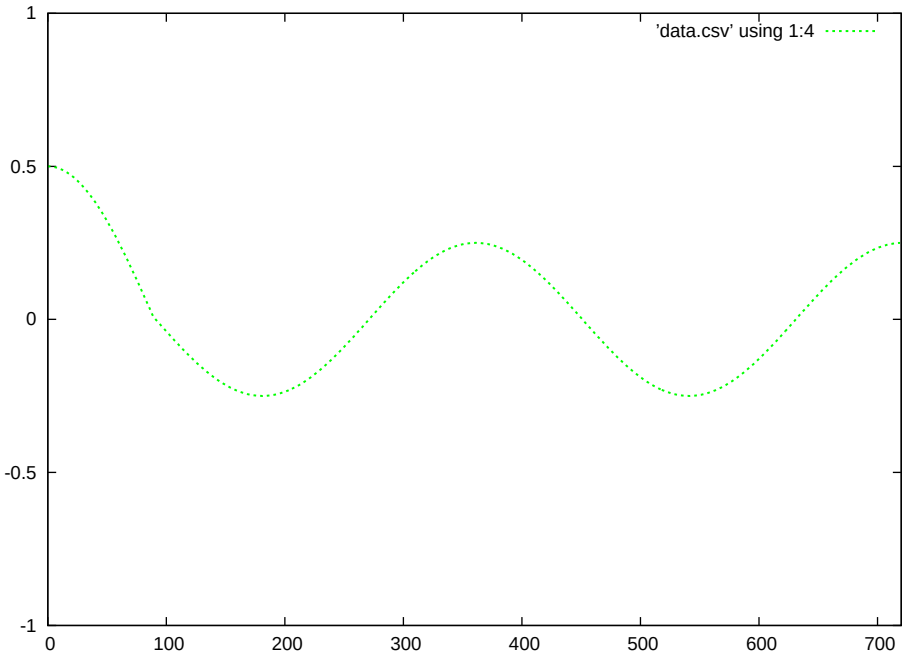
Green = superposition of the forward and reflected waves



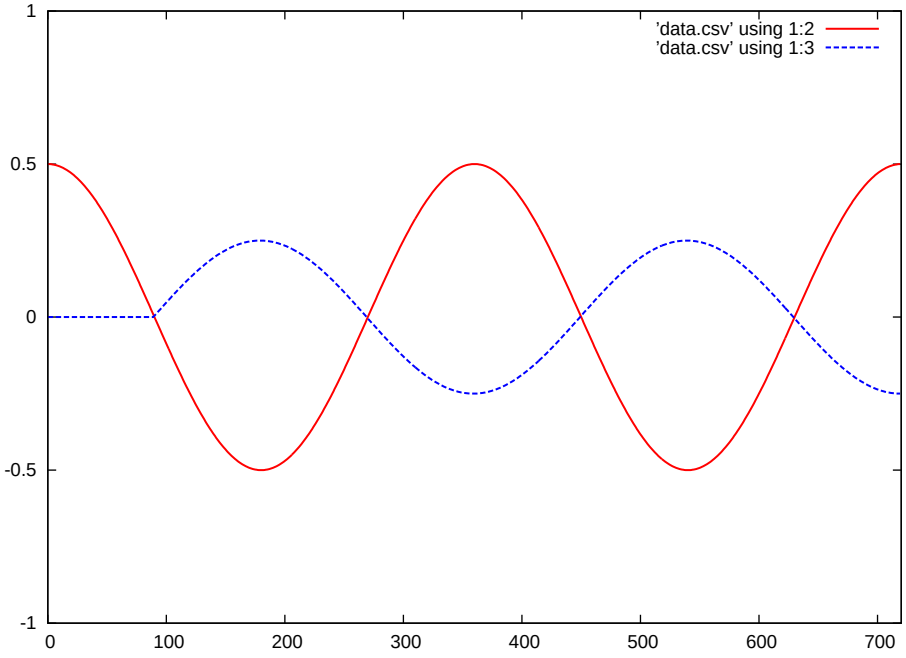
Red = forward wave Blue = reflected wave



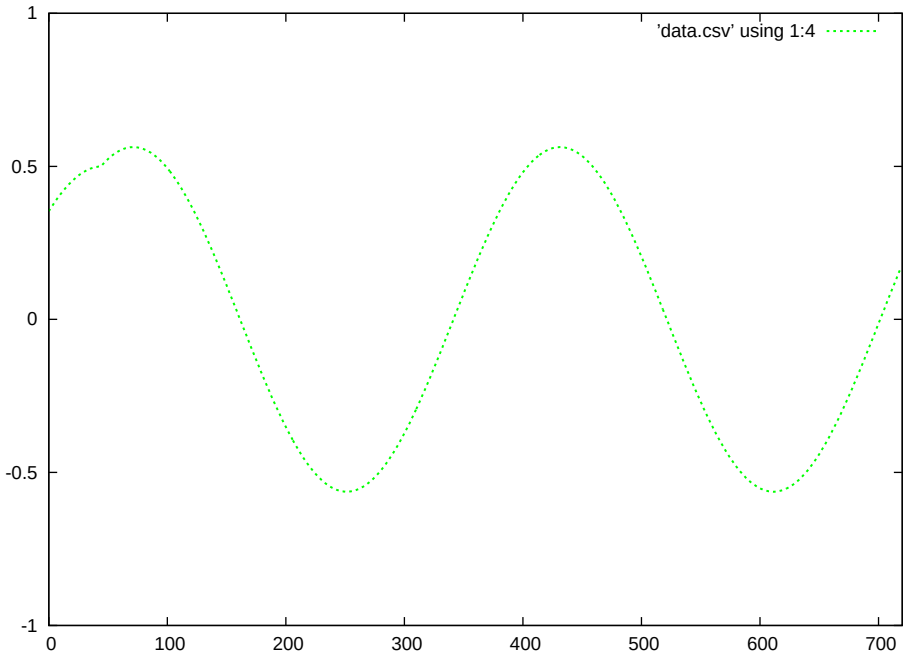
Green = superposition of the forward and reflected waves



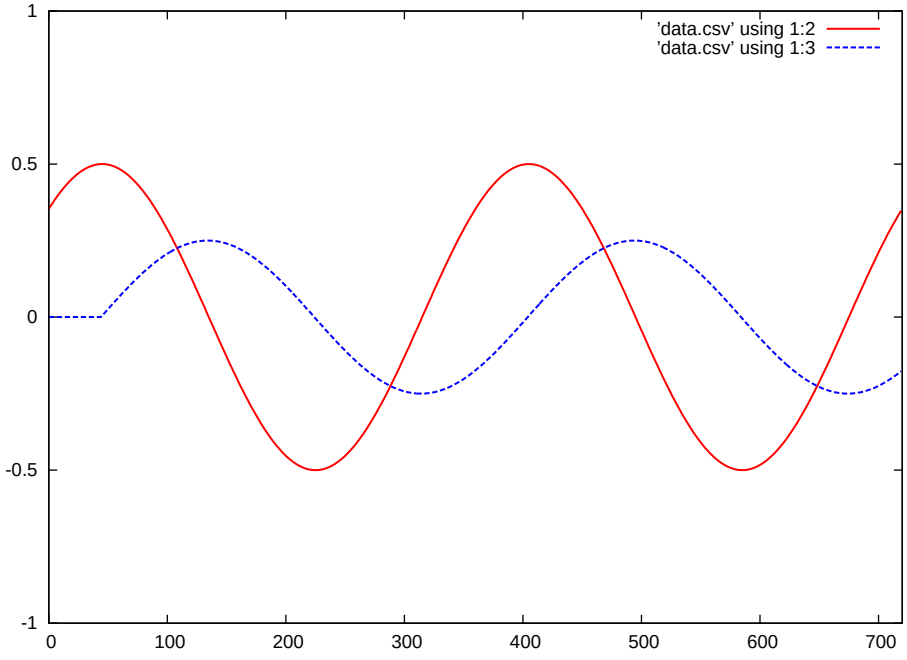
Red = forward wave Blue = reflected wave



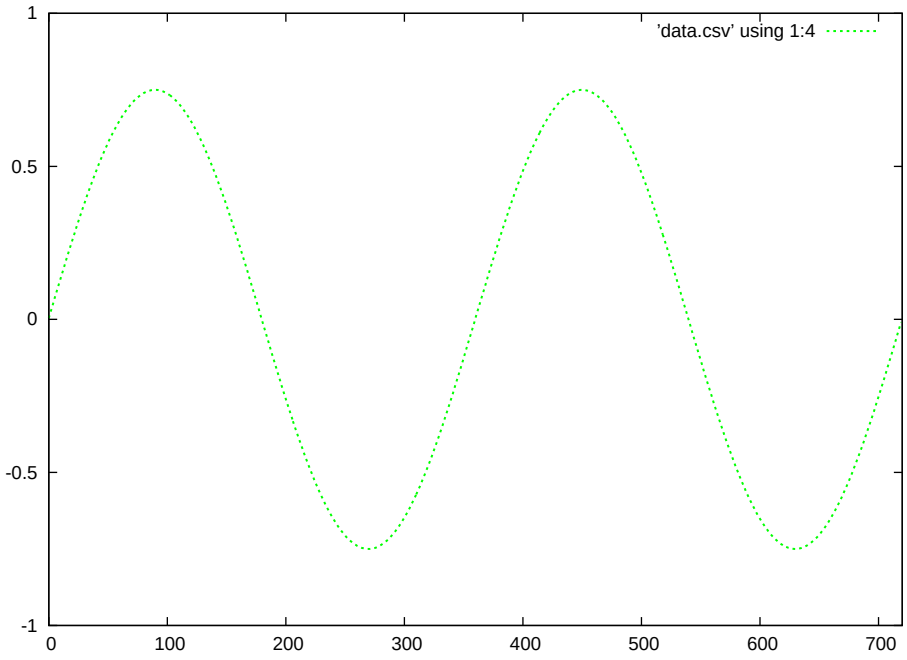
Green = superposition of the forward and reflected waves



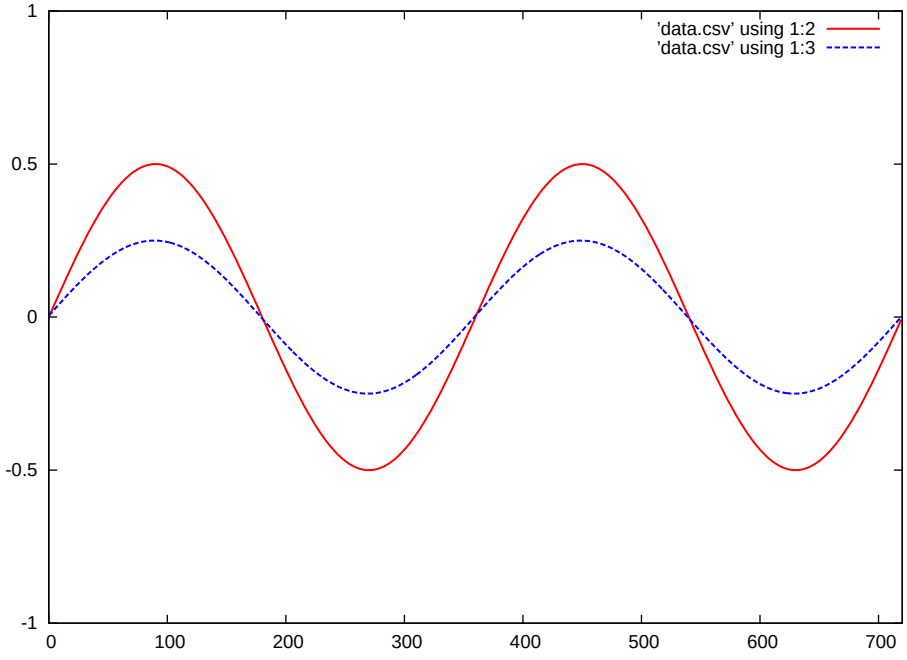
Red = forward wave Blue = reflected wave



Green = superposition of the forward and reflected waves

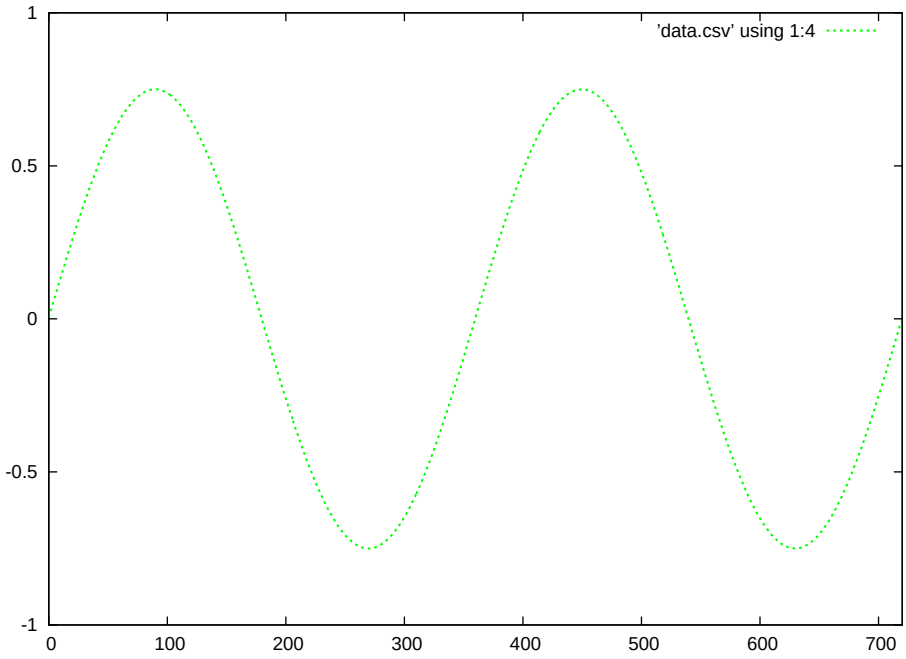


Red = forward wave Blue = reflected wave

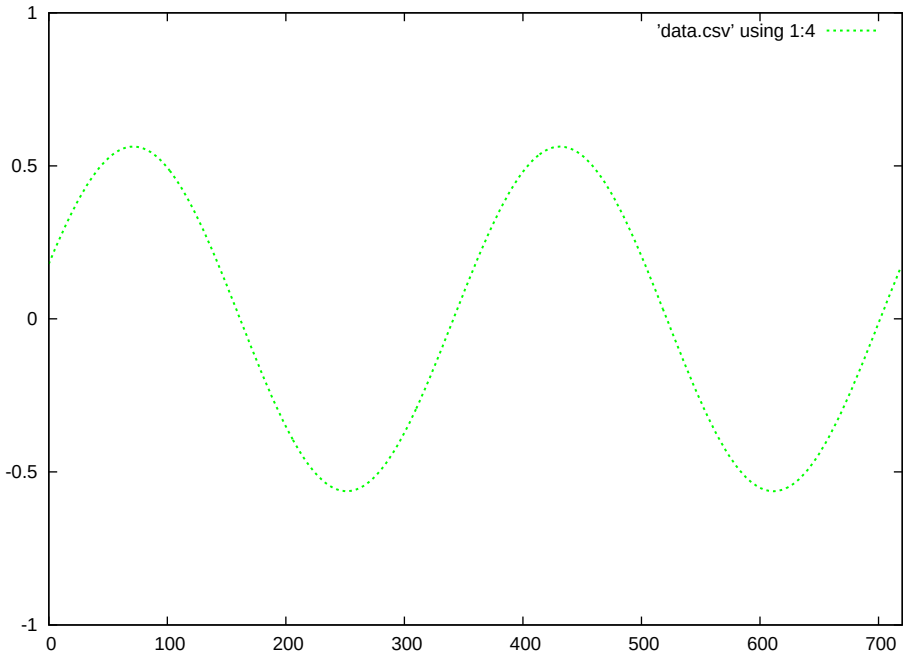


After the reflected wave has traveled all the way back to the source (left-hand end of the transmission line), the superposition of those two continuous waves results in a standing wave.

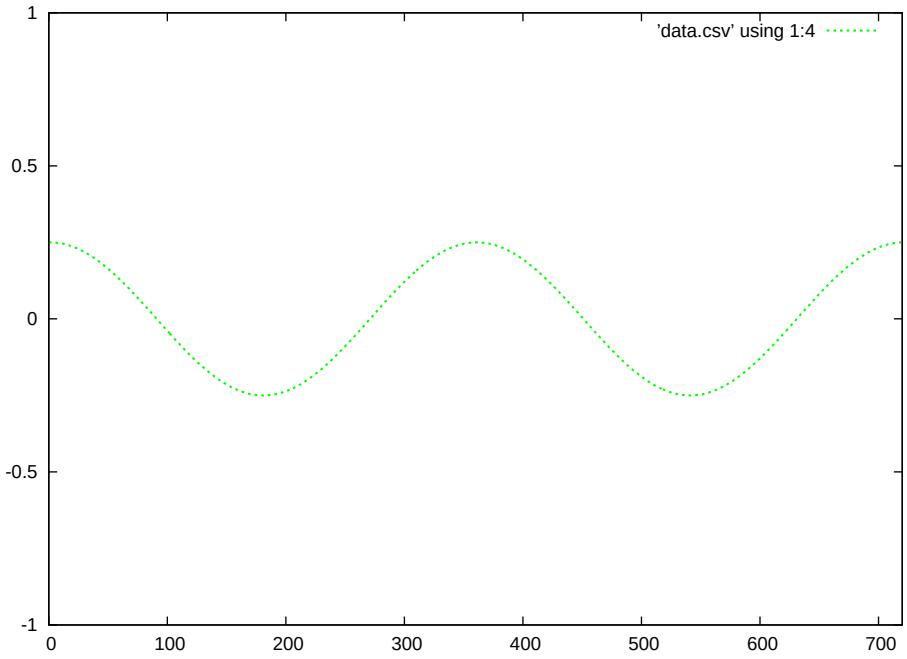
Green = standing wave



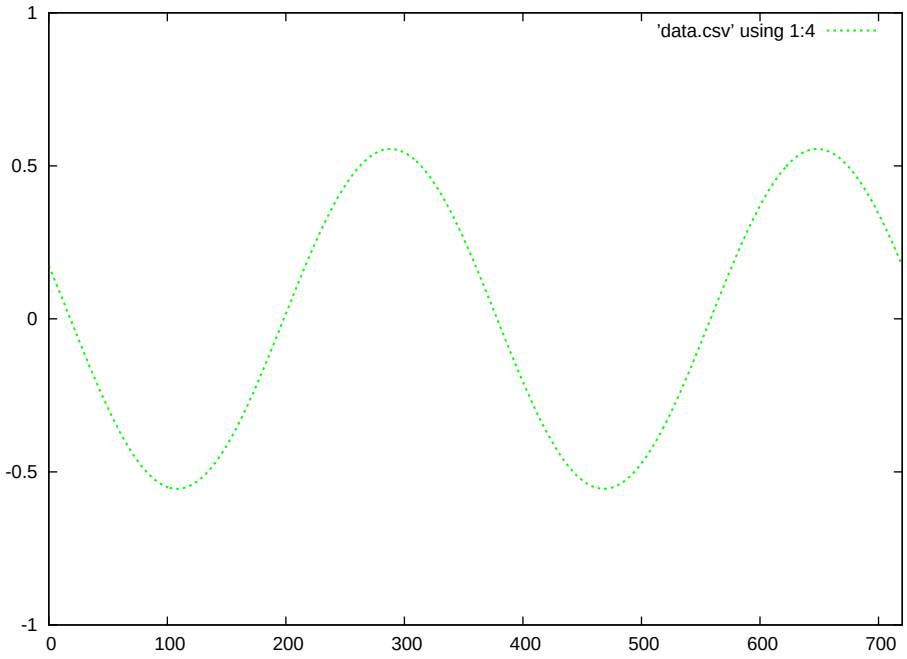
Green = standing wave



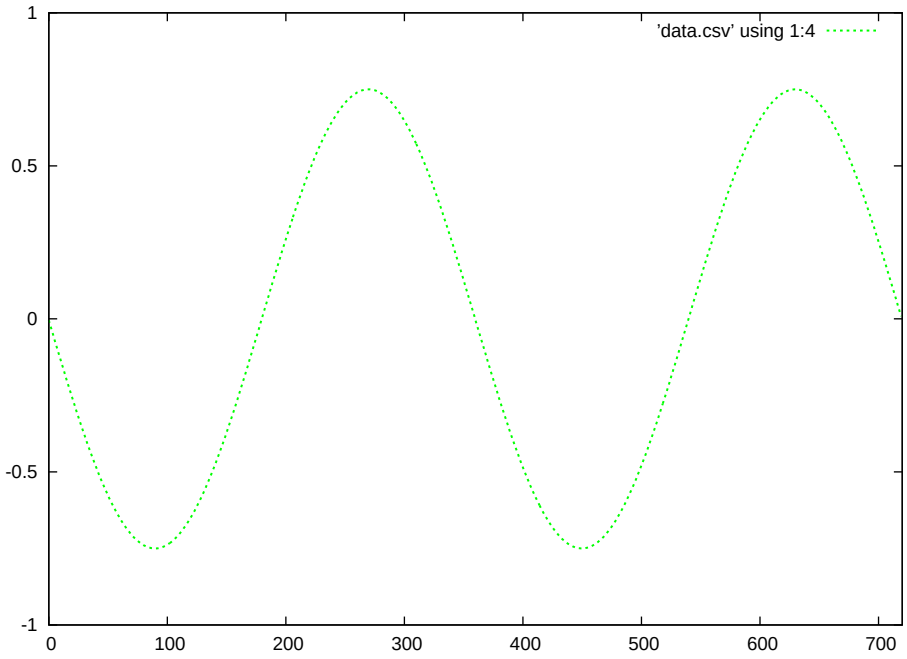
Green = standing wave



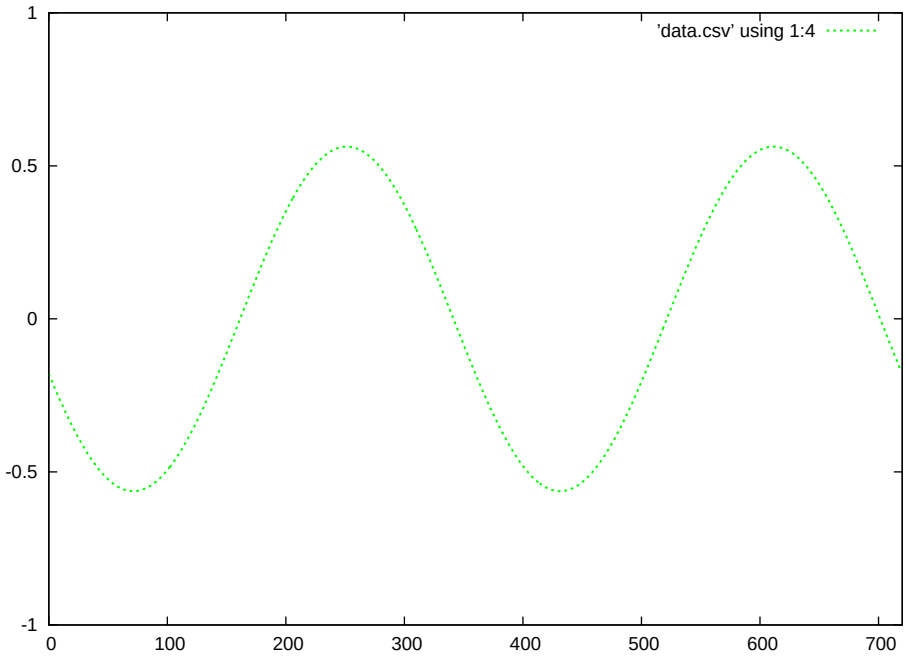
Green = standing wave



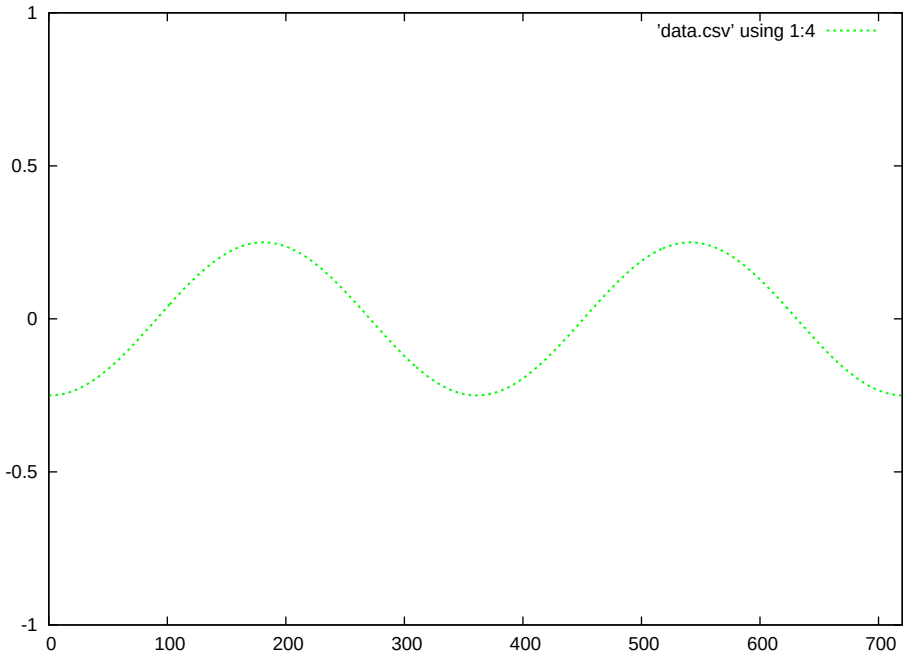
Green = standing wave



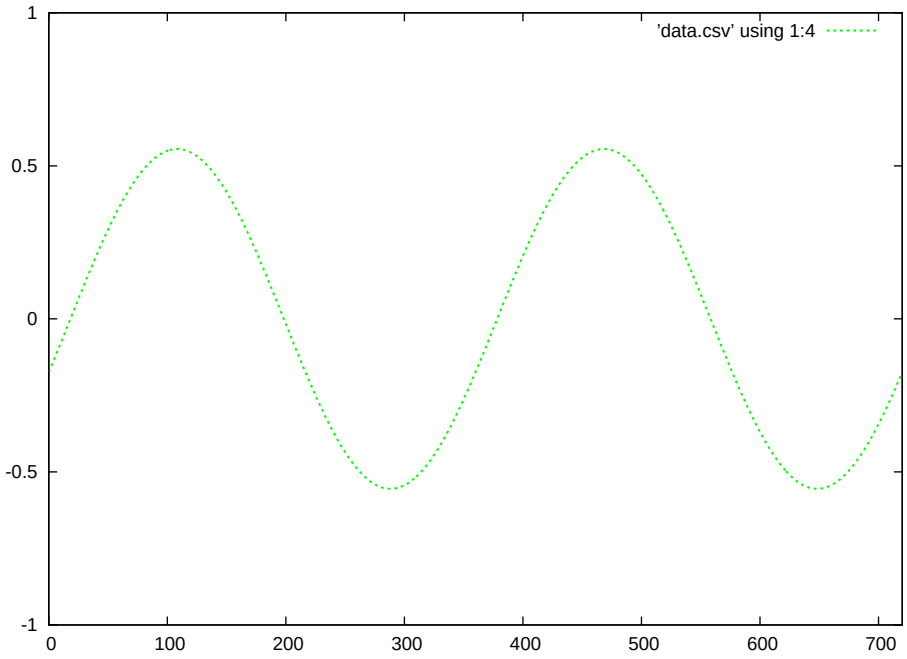
Green = standing wave



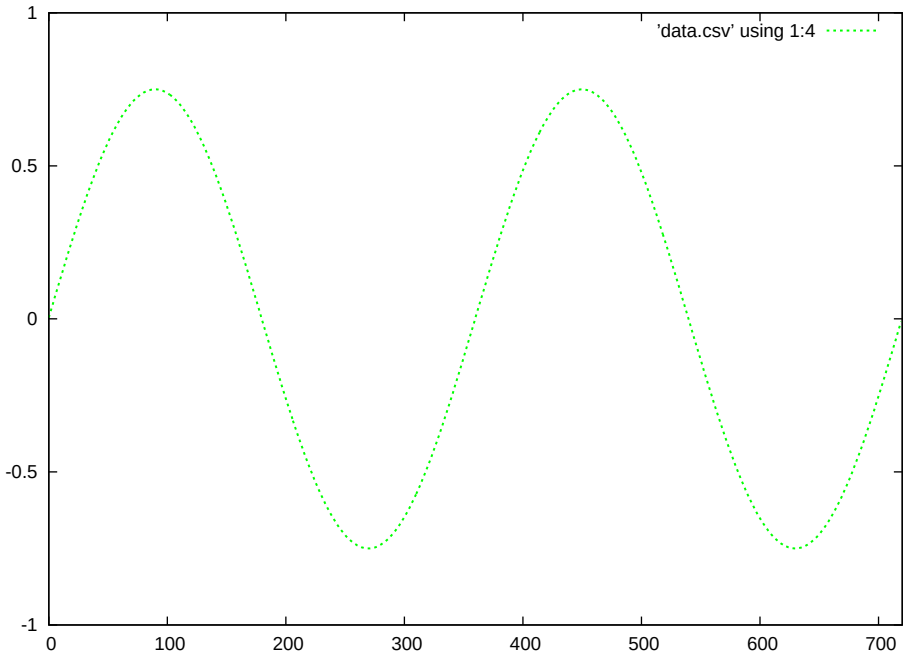
Green = standing wave



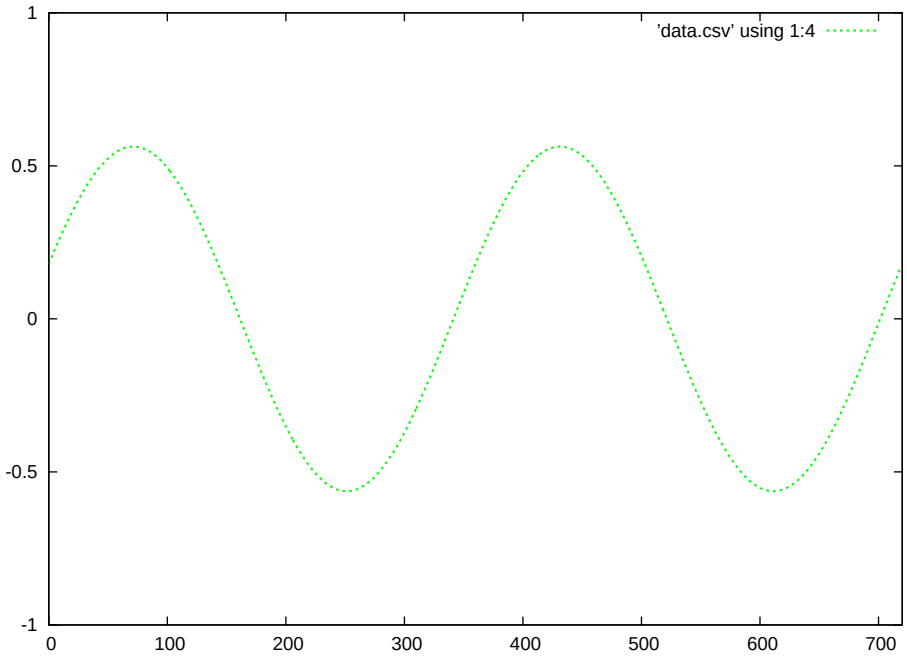
Green = standing wave



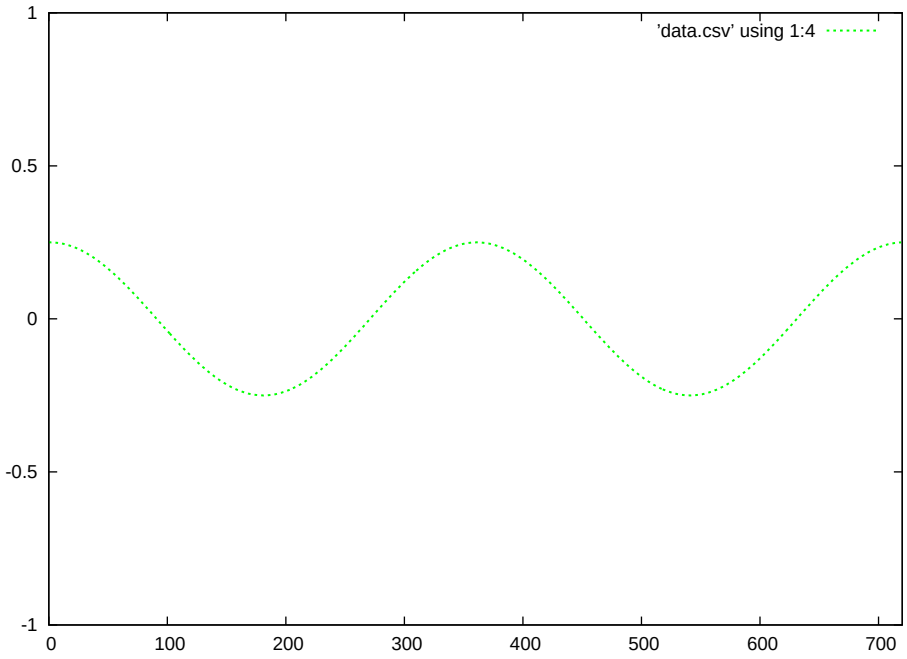
Green = standing wave



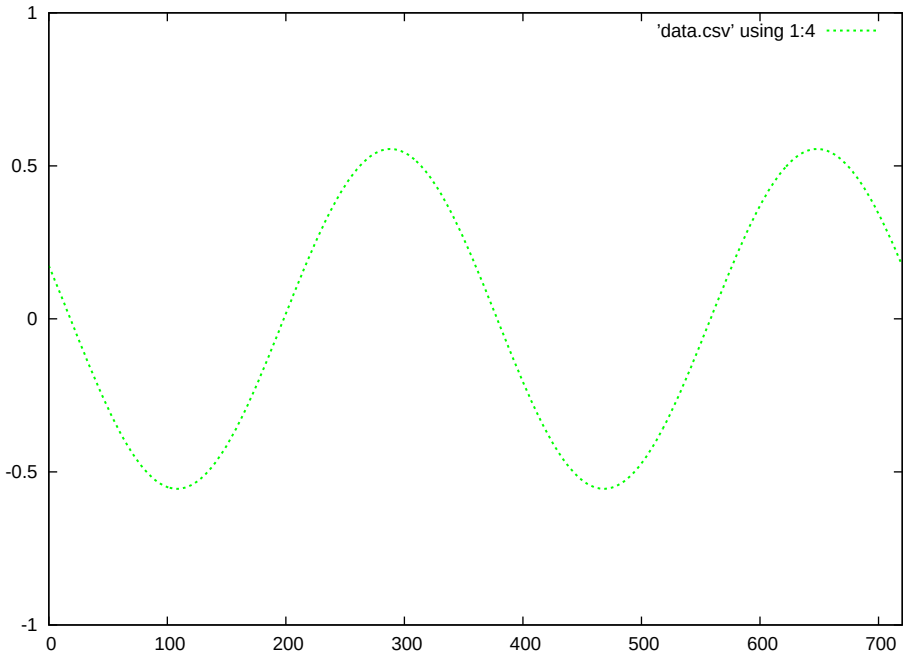
Green = standing wave



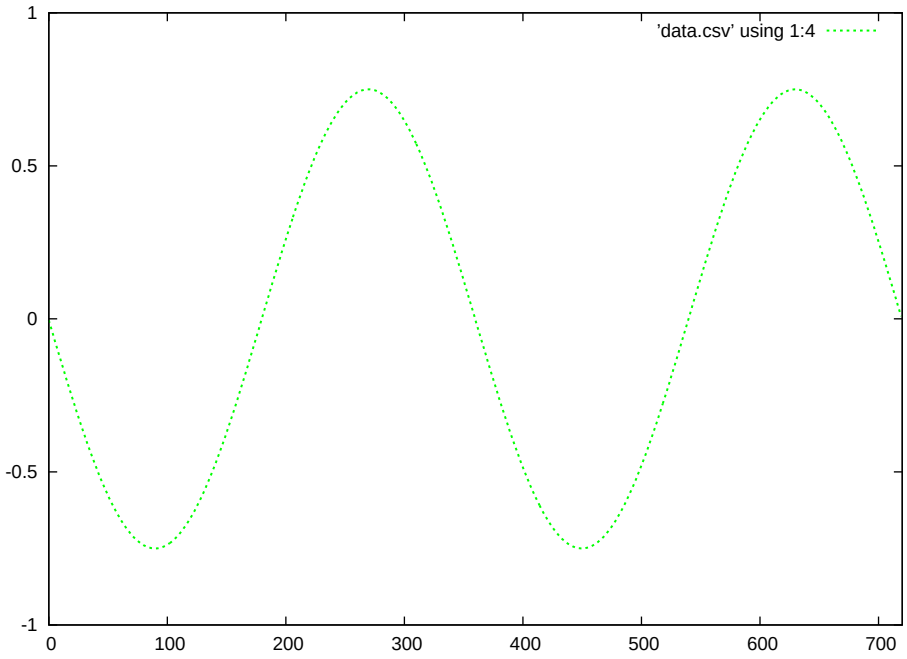
Green = standing wave



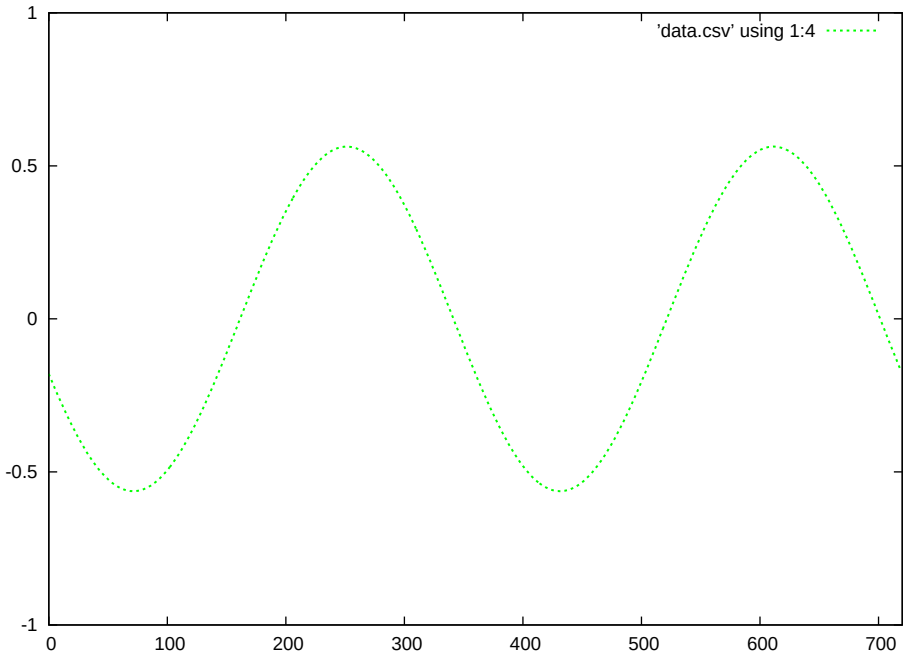
Green = standing wave



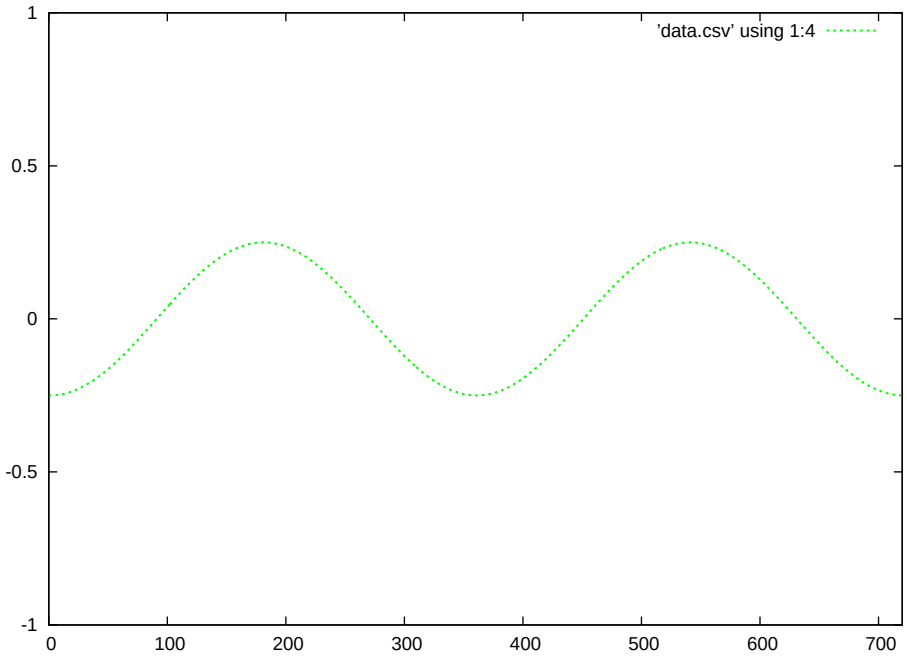
Green = standing wave



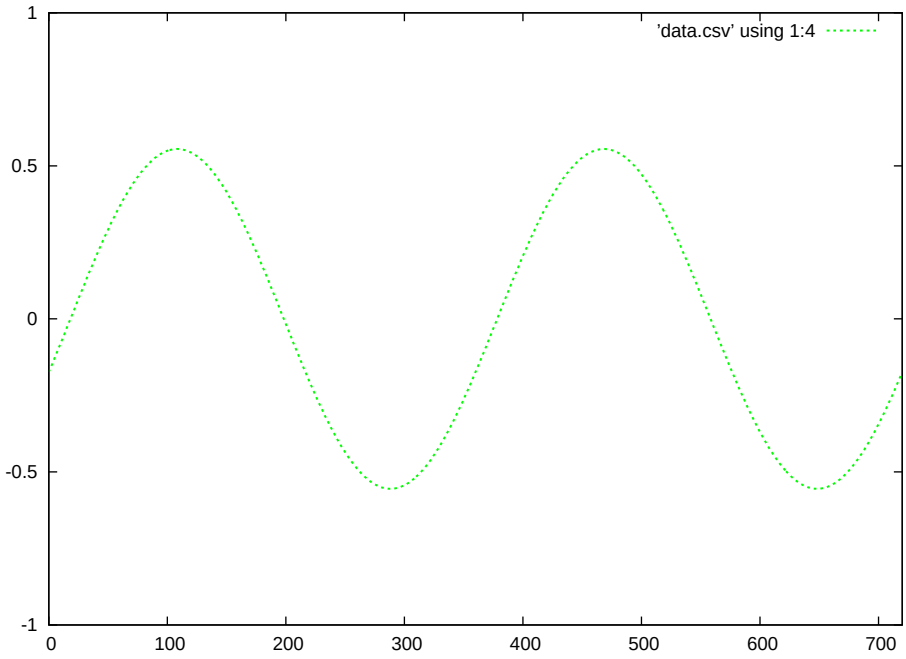
Green = standing wave



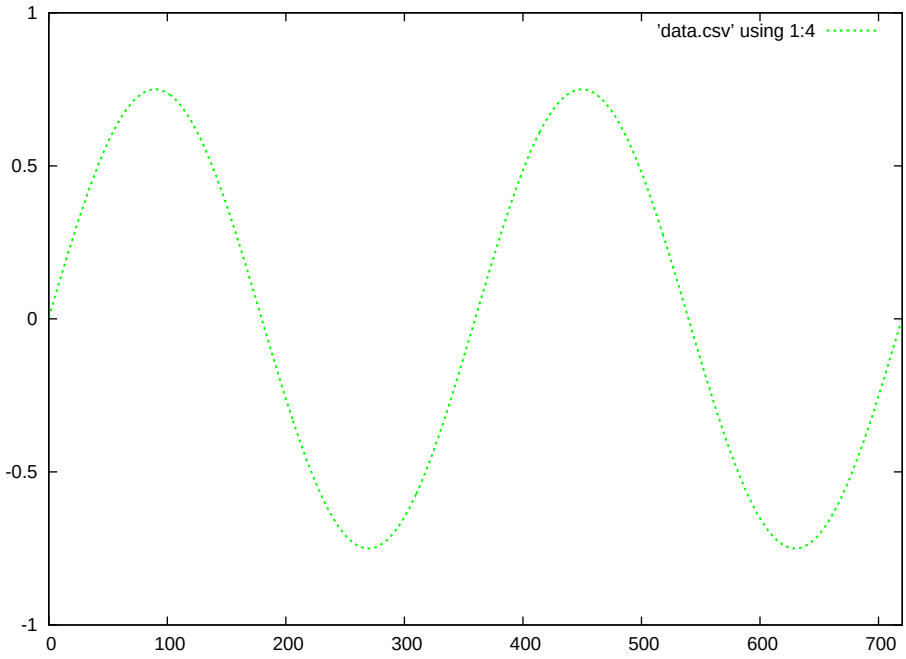
Green = standing wave



Green = standing wave



Green = standing wave



C++ source code for initial forward, reflected, and superposition waveforms with 50% reflection

```
#include <iostream>
#include <cmath>
using namespace std;

float sinecalc (int);

int main (void)
{
  int x, offset;
  float fwd[1440];
  float ref[720];
  float sum[720];

  offset = 1440;

  for (x = 0 ; x < 1440 ; ++x)
  {
    fwd[x] = 0.5*sinecalc(x-offset);
  }

  for (x = 0 ; x < 720 ; ++x)
  {
    if (offset <= 720)
    {
      ref[x] = 0.0;
      sum[x] = 0.0;
    }

    else
    {
      ref[719-x] = -0.5 * fwd[720+x];
    }
  }

  for (x = 0 ; x < 720 ; ++x)
  {
    sum[x] = fwd[x] + ref[x];
    cout << x << " , " << fwd[x] << " , " << ref[x] << " , " << sum[x] << endl;
  }

  return 0;
}
```

```
float sinecalc (int degrees)
{
  if (degrees < 0)
    return sin (degrees * M_PI / 180);

  else
    return 0.0;
}
```

Running this exact program produces a set of text-based data, separated by commas, representing the forward, reflected, and summation waves at an angle of 1440 degrees.

Gnuplot source code (named `gnuplot.txt`)

```
set datafile separator ","  # Interpret commas as field separators
set term postscript eps
set xrange [0:720]  # Sets bounds on the domain
set yrange [-1:1]  # Sets bounds on the domain
set style line 1 lw 3 lc rgb "red"  # Sets ls 1 thickness=3 color=red
set style line 2 lw 3 lc rgb "blue"  # Sets ls 2 thickness=3 color=blue
set style line 3 lw 3 lc rgb "green"  # Sets ls 3 thickness=3 color=green
set output 'anim_sw_fr_50_1440.eps'
plot 'data.csv' using 1:2 with lines ls 1, 'data.csv' using 1:3 with lines ls 2
set output 'anim_sw_sum_50_1440.eps'
plot 'data.csv' using 1:4 with lines ls 3
```

Note: the C++ program when compiled and run outputs comma-separated value (CVS) to the console (standard output). That C++ program must be compiled and run over and over again, each time with a different `offset` value representing the number of degrees the two waveforms have evolved over. For each run of the C++ program, I used Gnuplot to convert the comma-separated text file into graphical images, editing the gnuplot script each time to re-name the files according to the offset (angle) value. To convert this text data into graphical plots, you must redirect the output to a file (I use the filename `data.csv`) like this:

```
./a.out > data.csv
```

Then, you invoke Gnuplot to convert this text data into two Encapsulated PostScript files like so:

```
gnuplot -p gnuplot.txt
```

Gnuplot must be run once per execution of the C++ code, each time producing a pair of graphical images. The first image shows both the forward and reflected waves at that angle (`offset`), and the second image showing just the summation of the forward and reflected waves at that angle.

C++ source code for established standing waveform with 50% reflection

```
#include <iostream>
#include <cmath>
using namespace std;

float sinecalc (int);

int main (void)
{
  int x, offset;
  float fwd[720];
  float ref[720];
  float sum[720];

  offset = 360;

  for (x = 0 ; x < 720 ; ++x)
  {
    fwd[x] = 0.5*sinecalc(x+offset);
    ref[719-x] = -0.25*sinecalc(x+offset);
  }

  for (x = 0 ; x < 720 ; ++x)
  {
    sum[x] = fwd[x] + ref[x];
  }

  for (x = 0 ; x < 720 ; ++x)
  {
    cout << x << " , " << fwd[x] << " , " << ref[x] << " , " << sum[x] << endl;
  }

  return 0;
}

float sinecalc (int degrees)
{
    return sin (degrees * M_PI / 180);
}
```

As before, this C++ code must be compiled and executed repeatedly, each time with a different offset value. The only difference here is that the offset values need only span from 0 to 360 degrees,

not all the way to 1440 degrees as before to simulate the initial travel of both the forward and reflected waves along the transmission line's length.

Chapter 6

Questions

This learning module, along with all others in the ModEL collection, is designed to be used in an inverted instructional environment where students independently read[1] the tutorials and attempt to answer questions on their own *prior* to the instructor's interaction with them. In place of lecture[2], the instructor engages with students in Socratic-style dialogue, probing and challenging their understanding of the subject matter through inquiry.

Answers are not provided for questions within this chapter, and this is by design. Solved problems may be found in the Tutorial and Derivation chapters, instead. The goal here is *independence*, and this requires students to be challenged in ways where others cannot think for them. Remember that you always have the tools of *experimentation* and *computer simulation* (e.g. SPICE) to explore concepts!

The following lists contain ideas for Socratic-style questions and challenges. Upon inspection, one will notice a strong theme of *metacognition* within these statements: they are designed to foster a regular habit of examining one's own thoughts as a means toward clearer thinking. As such these sample questions are useful both for instructor-led discussions as well as for self-study.

[1] Technical reading is an essential academic skill for any technical practitioner to possess for the simple reason that the most comprehensive, accurate, and useful information to be found for developing technical competence is in textual form. Technical careers in general are characterized by the need for continuous learning to remain current with standards and technology, and therefore any technical practitioner who cannot read well is handicapped in their professional development. An excellent resource for educators on improving students' reading prowess through intentional effort and strategy is the book textitReading For Understanding – How Reading Apprenticeship Improves Disciplinary Learning in Secondary and College Classrooms by Ruth Schoenbach, Cynthia Greenleaf, and Lynn Murphy.

[2] Lecture is popular as a teaching method because it is easy to implement: any reasonably articulate subject matter expert can talk to students, even with little preparation. However, it is also quite problematic. A good lecture always makes complicated concepts seem easier than they are, which is bad for students because it instills a false sense of confidence in their own understanding; reading and re-articulation requires more cognitive effort and serves to verify comprehension. A culture of teaching-by-lecture fosters a debilitating dependence upon direct personal instruction, whereas the challenges of modern life demand independent and critical thought made possible only by gathering information and perspectives from afar. Information presented in a lecture is ephemeral, easily lost to failures of memory and dictation; text is forever, and may be referenced at any time.

General challenges following tutorial reading

- Summarize as much of the text as you can in one paragraph of your own words. A helpful strategy is to explain ideas as you would for an intelligent child: as simple as you can without compromising too much accuracy.
- Simplify a particular section of the text, for example a paragraph or even a single sentence, so as to capture the same fundamental idea in fewer words.
- Where did the text make the most sense to you? What was it about the text's presentation that made it clear?
- Identify where it might be easy for someone to misunderstand the text, and explain why you think it could be confusing.
- Identify any new concept(s) presented in the text, and explain in your own words.
- Identify any familiar concept(s) such as physical laws or principles applied or referenced in the text.
- Devise a proof of concept experiment demonstrating an important principle, physical law, or technical innovation represented in the text.
- Devise an experiment to disprove a plausible misconception.
- Did the text reveal any misconceptions you might have harbored? If so, describe the misconception(s) and the reason(s) why you now know them to be incorrect.
- Describe any useful problem-solving strategies applied in the text.
- Devise a question of your own to challenge a reader's comprehension of the text.

General follow-up challenges for assigned problems

- Identify where any fundamental laws or principles apply to the solution of this problem, especially before applying any mathematical techniques.
- Devise a thought experiment to explore the characteristics of the problem scenario, applying known laws and principles to mentally model its behavior.
- Describe in detail your own strategy for solving this problem. How did you identify and organized the given information? Did you sketch any diagrams to help frame the problem?
- Is there more than one way to solve this problem? Which method seems best to you?
- Show the work you did in solving this problem, even if the solution is incomplete or incorrect.
- What would you say was the most challenging part of this problem, and why was it so?
- Was any important information missing from the problem which you had to research or recall?
- Was there any extraneous information presented within this problem? If so, what was it and why did it not matter?
- Examine someone else's solution to identify where they applied fundamental laws or principles.
- Simplify the problem from its given form and show how to solve this simpler version of it. Examples include eliminating certain variables or conditions, altering values to simpler (usually whole) numbers, applying a limiting case (i.e. altering a variable to some extreme or ultimate value).
- For quantitative problems, identify the real-world meaning of all intermediate calculations: their units of measurement, where they fit into the scenario at hand. Annotate any diagrams or illustrations with these calculated values.
- For quantitative problems, try approaching it qualitatively instead, thinking in terms of "increase" and "decrease" rather than definite values.
- For qualitative problems, try approaching it quantitatively instead, proposing simple numerical values for the variables.
- Were there any assumptions you made while solving this problem? Would your solution change if one of those assumptions were altered?
- Identify where it would be easy for someone to go astray in attempting to solve this problem.
- Formulate your own problem based on what you learned solving this one.

General follow-up challenges for experiments or projects

- In what way(s) was this experiment or project easy to complete?
- Identify some of the challenges you faced in completing this experiment or project.

- Show how thorough documentation assisted in the completion of this experiment or project.
- Which fundamental laws or principles are key to this system's function?
- Identify any way(s) in which one might obtain false or otherwise misleading measurements from test equipment in this system.
- What will happen if (component X) fails (open/shorted/etc.)?
- What would have to occur to make this system unsafe?

6.1 Conceptual reasoning

These questions are designed to stimulate your analytic and synthetic thinking[3]. In a Socratic discussion with your instructor, the goal is for these questions to prompt an extended dialogue where assumptions are revealed, conclusions are tested, and understanding is sharpened. Your instructor may also pose additional questions based on those assigned, in order to further probe and refine your conceptual understanding.

Questions that follow are presented to challenge and probe your understanding of various concepts presented in the tutorial. These questions are intended to serve as a guide for the Socratic dialogue between yourself and the instructor. Your instructor's task is to ensure you have a sound grasp of these concepts, and the questions contained in this document are merely a means to this end. Your instructor may, at his or her discretion, alter or substitute questions for the benefit of tailoring the discussion to each student's needs. The only absolute requirement is that each student is challenged and assessed at a level equal to or greater than that represented by the documented questions.

It is far more important that you convey your *reasoning* than it is to simply convey a correct answer. For this reason, you should refrain from researching other information sources to answer questions. What matters here is that *you* are doing the thinking. If the answer is incorrect, your instructor will work with you to correct it through proper reasoning. A correct answer without an adequate explanation of how you derived that answer is unacceptable, as it does not aid the learning or assessment process.

You will note a conspicuous lack of answers given for these conceptual questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your conceptual answers, where applicable, is to use circuit simulation software to explore the effects of changes made to circuits. For example, if one of these conceptual questions challenges you to predict the effects of altering some component parameter in a circuit, you may check the validity of your work by simulating that same parameter change within software and seeing if the results agree.

[3] *Analytical* thinking involves the "disassembly" of an idea into its constituent parts, analogous to dissection. *Synthetic* thinking involves the "assembly" of a new idea comprised of multiple concepts, analogous to construction. Both activities are high-level cognitive skills, extremely important for effective problem-solving, necessitating frequent challenge and regular practice to fully develop.

6.1.1 Reading outline and reflections

"Reading maketh a full man; conference a ready man; and writing an exact man" – Francis Bacon

Francis Bacon's advice is a blueprint for effective education: reading provides the learner with knowledge, writing focuses the learner's thoughts, and critical dialogue equips the learner to confidently communicate and apply their learning. Independent acquisition and application of knowledge is a powerful skill, well worth the effort to cultivate. To this end, students should read these educational resources closely, journal their own reflections on the reading, and discuss in detail their findings with classmates and instructor(s). You should be able to do all of the following after reading any instructional text:

☑ Briefly SUMMARIZE THE TEXT in the form of a journal entry documenting your learning as you progress through the course of study. Share this summary in dialogue with your classmates and instructor. Journaling is an excellent self-test of thorough reading because you cannot clearly express what you have not read or did not comprehend.

☑ Demonstrate ACTIVE READING STRATEGIES, including verbalizing your impressions as you read, simplifying long passages to convey the same ideas using fewer words, annotating text and illustrations with your own interpretations, working through mathematical examples shown in the text, cross-referencing passages with relevant illustrations and/or other passages, identifying problem-solving strategies applied by the author, etc. Technical reading is a special case of problem-solving, and so these strategies work precisely because they help solve any problem: paying attention to your own thoughts (metacognition), eliminating unnecessary complexities, identifying what makes sense, paying close attention to details, drawing connections between separated facts, and noting the successful strategies of others.

☑ Identify IMPORTANT THEMES, especially GENERAL LAWS and PRINCIPLES, expounded in the text and express them in the simplest of terms as though you were teaching an intelligent child. This emphasizes connections between related topics and develops your ability to communicate complex ideas to anyone.

☑ Form YOUR OWN QUESTIONS based on the reading, and then pose them to your instructor and classmates for their consideration. Anticipate both correct and incorrect answers, the incorrect answer(s) assuming one or more plausible misconceptions. This helps you view the subject from different perspectives to grasp it more fully.

☑ Devise EXPERIMENTS to test claims presented in the reading, or to disprove misconceptions. Predict possible outcomes of these experiments, and evaluate their meanings: what result(s) would confirm, and what would constitute disproof? Running mental simulations and evaluating results is essential to scientific and diagnostic reasoning.

☑ Specifically identify any points you found CONFUSING. The reason for doing this is to help diagnose misconceptions and overcome barriers to learning.

6.1.2 Foundational concepts

Correct analysis and diagnosis of electric circuits begins with a proper understanding of some basic concepts. The following is a list of some important concepts referenced in this module's full tutorial. Define each of them in your own words, and be prepared to illustrate each of these concepts with a description of a practical example and/or a live demonstration.

Electrical source

Electrical load

Ohm's Law

Parasitic effect

Capacitance

Inductance

Electric field

Magnetic field

Electromagnetic wave

Antenna

Frequency

Wavelength

Resonance

Dipole

Monopole

Radiation pattern

Radiation resistance

Modulation

Demodulation

Harmonic frequency

Filter

Thévenin's theorem

Transmission line

Signal reflection

Characteristic or Surge impedance

Coaxial line

Twin-lead line

Waveguide

Standing wave

Standing Wave Ratio (SWR)

Nodes and antinodes

Electromagnetic induction

Mutual induction

Transformer

Primary winding

Secondary winding

Matching section

Balanced signal

Unbalanced signal

Balun

6.1.3 Optimum standing wave ratio

Suppose a radio operator has a pair of meters to measure feedline power: one showing forward power and the other showing reflected power. What should these two meters register when the SWR is optimum?

Challenges

- What constitutes a poor SWR?
- Why is a poor SWR bad for an operating RF system?

6.1.4 Adjusting twin-lead impedance

One of the advantages of twin-lead feedline is that it may be constructed in custom impedance values from individual wires and insulating spacers. Supposing we wished to modify an existing twin-lead feedline to have a greater characteristic impedance, how could we re-build it?

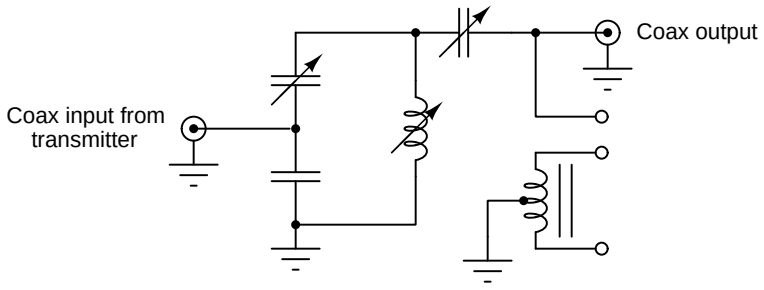
Challenges

- What causes a transmission line to have a specific characteristic (surge) impedance?

6.1.5 Ultimate Transmatch

Lewis McCoy's "Ultimate Transmatch" impedance-matching circuit was capable of both balanced and unbalanced output to the feedline, from the unbalanced signal output by the transmitter.

Lew McCoy's "Ultimate Transmatch"



Sketch connections from the output terminals of the Transmatch network to three different types of antenna:

- Single-wire (long-wire antenna)
- Monopole with coaxial feedline
- Dipole with twin-lead feedline

Challenges

- Is the Ultimate Transmatch network frequency-dependent? That is, will it need to be adjusted for different frequencies of transceiver operation?

6.2 Quantitative reasoning

These questions are designed to stimulate your computational thinking. In a Socratic discussion with your instructor, the goal is for these questions to reveal your mathematical approach(es) to problem-solving so that good technique and sound reasoning may be reinforced. Your instructor may also pose additional questions based on those assigned, in order to observe your problem-solving firsthand.

Mental arithmetic and estimations are strongly encouraged for all calculations, because without these abilities you will be unable to readily detect errors caused by calculator misuse (e.g. keystroke errors).

You will note a conspicuous lack of answers given for these quantitative questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. My advice is to use circuit simulation software such as SPICE to check the correctness of quantitative answers. Refer to those learning modules within this collection focusing on SPICE to see worked examples which you may use directly as practice problems for your own study, and/or as templates you may modify to run your own analyses and generate your own practice problems.

Completely worked example problems found in the Tutorial may also serve as "test cases[4]" for gaining proficiency in the use of circuit simulation software, and then once that proficiency is gained you will never need to rely[5] on an answer key!

[4] In other words, set up the circuit simulation software to analyze the same circuit examples found in the Tutorial. If the simulated results match the answers shown in the Tutorial, it confirms the simulation has properly run. If the simulated results disagree with the Tutorial's answers, something has been set up incorrectly in the simulation software. Using every Tutorial as practice in this way will quickly develop proficiency in the use of circuit simulation software.

[5] This approach is perfectly in keeping with the instructional philosophy of these learning modules: *teaching students to be self-sufficient thinkers*. Answer keys can be useful, but it is even more useful to your long-term success to have a set of tools on hand for checking your own work, because once you have left school and are on your own, there will no longer be "answer keys" available for the problems you will have to solve.

6.2.1 Miscellaneous physical constants

Note: constants shown in **bold** type are *exact*, not approximations. Values inside of parentheses show one standard deviation (σ) of uncertainty in the final digits: for example, the magnetic permeability of free space value given as $1.25663706212(19) \times 10^{-6}$ H/m represents a center value (i.e. the location parameter) of $1.25663706212 \times 10^{-6}$ Henrys per meter with one standard deviation of uncertainty equal to $0.0000000000019 \times 10^{-6}$ Henrys per meter.

Avogadro's number (N_A) = **6.02214076** $\times 10^{23}$ **per mole** (mol^{-1})

Boltzmann's constant (k) = **1.380649** $\times 10^{-23}$ **Joules per Kelvin** (J/K)

Electronic charge (e) = **1.602176634** $\times 10^{-19}$ **Coulomb** (C)

Faraday constant (F) = **96,485.33212...** $\times 10^{4}$ **Coulombs per mole** (C/mol)

Magnetic permeability of free space (μ_0) = 1.25663706212(19) $\times 10^{-6}$ Henrys per meter (H/m)

Electric permittivity of free space (ϵ_0) = 8.8541878128(13) $\times 10^{-12}$ Farads per meter (F/m)

Characteristic impedance of free space (Z_0) = 376.730313668(57) Ohms (Ω)

Gravitational constant (G) = 6.67430(15) $\times 10^{-11}$ cubic meters per kilogram-seconds squared ($m^3/kg\text{-}s^2$)

Molar gas constant (R) = **8.314462618... Joules per mole-Kelvin** (J/mol-K) = 0.08205746(14) liters-atmospheres per mole-Kelvin

Planck constant (h) = **6.62607015** $\times 10^{-34}$ **joule-seconds** (J-s)

Stefan-Boltzmann constant (σ) = **5.670374419...** $\times 10^{-8}$ **Watts per square meter-Kelvin**^{4} ($W/m^2 \cdot K^4$)

Speed of light in a vacuum (c) = **299,792,458 meters per second** (m/s) = 186282.4 miles per second (mi/s)

Note: All constants taken from NIST data "Fundamental Physical Constants – Complete Listing", from `http://physics.nist.gov/constants`, National Institute of Standards and Technology (NIST), 2018 CODATA Adjustment.

6.2.2 Introduction to spreadsheets

A powerful computational tool you are encouraged to use in your work is a *spreadsheet*. Available on most personal computers (e.g. Microsoft Excel), *spreadsheet* software performs numerical calculations based on number values and formulae entered into cells of a grid. This grid is typically arranged as lettered columns and numbered rows, with each cell of the grid identified by its column/row coordinates (e.g. cell `B3`, cell `A8`). Each cell may contain a string of text, a number value, or a mathematical formula. The spreadsheet automatically updates the results of all mathematical formulae whenever the entered number values are changed. This means it is possible to set up a spreadsheet to perform a series of calculations on entered data, and those calculations will be re-done by the computer any time the data points are edited in any way.

For example, the following spreadsheet calculates average speed based on entered values of distance traveled and time elapsed:

	A	B	C	D
1	Distance traveled	46.9	Kilometers	
2	Time elapsed	1.18	Hours	
3	Average speed	= B1 / B2	km/h	
4				
5				

Text labels contained in cells `A1` through `A3` and cells `C1` through `C3` exist solely for readability and are not involved in any calculations. Cell `B1` contains a sample distance value while cell `B2` contains a sample time value. The formula for computing speed is contained in cell `B3`. Note how this formula begins with an "equals" symbol (`=`), references the values for distance and speed by lettered column and numbered row coordinates (`B1` and `B2`), and uses a forward slash symbol for division (`/`). The coordinates `B1` and `B2` function as *variables*[6] would in an algebraic formula.

When this spreadsheet is executed, the numerical value `39.74576` will appear in cell `B3` rather than the formula `= B1 / B2`, because 39.74576 is the computed speed value given 46.9 kilometers traveled over a period of 1.18 hours. If a different numerical value for distance is entered into cell `B1` or a different value for time is entered into cell `B2`, cell `B3`'s value will automatically update. All you need to do is set up the given values and any formulae into the spreadsheet, and the computer will do all the calculations for you.

Cell `B3` may be referenced by other formulae in the spreadsheet if desired, since it is a variable just like the given values contained in `B1` and `B2`. This means it is possible to set up an entire chain of calculations, one dependent on the result of another, in order to arrive at a final value. The arrangement of the given data and formulae need not follow any pattern on the grid, which means you may place them anywhere.

[6] Spreadsheets may also provide means to attach text labels to cells for use as variable names (Microsoft Excel simply calls these labels "names"), but for simple spreadsheets such as those shown here it's usually easier just to use the standard coordinate naming for each cell.

Common[7] arithmetic operations available for your use in a spreadsheet include the following:

- Addition (`+`)
- Subtraction (`-`)
- Multiplication (`*`)
- Division (`/`)
- Powers (`^`)
- Square roots (`sqrt()`)
- Logarithms (`ln()` , `log10()`)

Parentheses may be used to ensure[8] proper order of operations within a complex formula. Consider this example of a spreadsheet implementing the *quadratic formula*, used to solve for roots of a polynomial expression in the form of $ax^2 + bx + c$:

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

	A	B
1	x_1	= (-B4 + sqrt((B4^2) - (4*B3*B5))) / (2*B3)
2	x_2	= (-B4 - sqrt((B4^2) - (4*B3*B5))) / (2*B3)
3	a =	9
4	b =	5
5	c =	-2

This example is configured to compute roots[9] of the polynomial $9x^2 + 5x - 2$ because the values of 9, 5, and -2 have been inserted into cells `B3`, `B4`, and `B5`, respectively. Once this spreadsheet has been built, though, it may be used to calculate the roots of *any* second-degree polynomial expression simply by entering the new a, b, and c coefficients into cells `B3` through `B5`. The numerical values appearing in cells `B1` and `B2` will be automatically updated by the computer immediately following any changes made to the coefficients.

[7] Modern spreadsheet software offers a bewildering array of mathematical functions you may use in your computations. I recommend you consult the documentation for your particular spreadsheet for information on operations other than those listed here.

[8] Spreadsheet programs, like text-based programming languages, are designed to follow standard order of operations by default. However, my personal preference is to use parentheses even where strictly unnecessary just to make it clear to any other person viewing the formula what the intended order of operations is.

[9] Reviewing some algebra here, a *root* is a value for x that yields an overall value of zero for the polynomial. For this polynomial ($9x^2 + 5x - 2$) the two roots happen to be $x = 0.269381$ and $x = -0.82494$, with these values displayed in cells `B1` and `B2`, respectively upon execution of the spreadsheet.

Alternatively, one could break up the long quadratic formula into smaller pieces like this:

$$y = \sqrt{b^2 - 4ac} \qquad z = 2a$$

$$x = \frac{-b \pm y}{z}$$

	A	B	C
1	x_1	= (-B4 + C1) / C2	= sqrt((B4^2) - (4*B3*B5))
2	x_2	= (-B4 - C1) / C2	= 2*B3
3	a =	9	
4	b =	5	
5	c =	-2	

Note how the square-root term (y) is calculated in cell C1, and the denominator term (z) in cell C2. This makes the two final formulae (in cells B1 and B2) simpler to interpret. The positioning of all these cells on the grid is completely arbitrary[10] – all that matters is that they properly reference each other in the formulae.

Spreadsheets are particularly useful for situations where the same set of calculations representing a circuit or other system must be repeated for different initial conditions. The power of a spreadsheet is that it automates what would otherwise be a tedious set of calculations. One specific application of this is to simulate the effects of various components within a circuit failing with abnormal values (e.g. a shorted resistor simulated by making its value nearly zero; an open resistor simulated by making its value extremely large). Another application is analyzing the behavior of a circuit design given new components that are out of specification, and/or aging components experiencing drift over time.

[10] My personal preference is to locate all the "given" data in the upper-left cells of the spreadsheet grid (each data point flanked by a sensible name in the cell to the left and units of measurement in the cell to the right as illustrated in the first distance/time spreadsheet example), sometimes coloring them in order to clearly distinguish which cells contain entered data versus which cells contain computed results from formulae. I like to place all formulae in cells below the given data, and try to arrange them in logical order so that anyone examining my spreadsheet will be able to figure out *how* I constructed a solution. This is a general principle I believe all computer programmers should follow: *document and arrange your code to make it easy for other people to learn from it.*

6.2.3 Proper line termination

A technician says that when properly terminating a transmission line, an impedance equal to the line's surge impedance needs to be connected at each end of the line. For example, if $Z_0 = \Omega$, there should be a 600 Ω impedance connected to one end of the line and another 600 Ω impedance connected to the other.

Another technician disagrees. They say doing so would result in an effective termination impedance of 300 Ω because those two impedances are in parallel with each other by virtue of being connected by the transmission line. Instead, they claim we need to terminate each end of the line with a *1200* Ω impedance so their combined total will be 600 Ω to match the line.

Which technician is correct? Why is the other conclusion wrong?

Challenges

- How may we measure the surge impedance of a line?

6.2.4 Transformer impedance ratios

Calculate each of the following parameters, assuming the other given conditions, for the following impedance-matching transformer examples:

- Primary turns = 50 ; Secondary turns = 35 ; Source impedance = 600 Ω ; Load impedance =
- Secondary turns = 40 ; Source impedance = 300 Ω ; Load impedance = 75 Ω ; Primary turns =
- Source impedance = 156.25 Ω ; Load impedance = 100 Ω ; Primary turns = 10 ; Secondary turns =
- Load impedance = 12 Ω ; Primary turns = 20 ; Secondary turns = 10 ; Source impedance =

Challenges

- Are any of these matching transformer scenarios frequency-dependent? That is, will the ratio need to be adjusted for different frequencies of transceiver operation?

6.2.5 Matching section

Suppose a 100 Ohm feedline needs to connect to a 300 Ohm antenna at a frequency of 85 MHz. Determine all the necessary parameters of the matching section to properly join these two.

Challenges

- What are some alternatives to a matching line section for this application?

6.2.6 Matching section calculator program

Complete this computer program (written in the C language) for calculating the necessary matching-section impedance to properly match a given transceiver with a given antenna:

```
#include <stdio.h>
#include <math.h>

int main (void)
{
  float Zxvr, Zant;

  printf("Enter the transceiver impedance in Ohms: ");
  scanf("%f", &Zxvr);

  printf("Enter the antenna impedance in Ohms: ");
  scanf("%f", &Zant);

  // Your code goes here

  return 0;
}
```

Also add lines of code to calculate the necessary length of this quarter-wavelength matching section assuming an operating frequency of 27 MHz using cable and a velocity factor of 0.69.

Challenges

- What are some alternative methods for matching transceiver and antenna impedances other than a matching section?

6.3 Diagnostic reasoning

These questions are designed to stimulate your deductive and inductive thinking, where you must apply general principles to specific scenarios (deductive) and also derive conclusions about the failed circuit from specific details (inductive). In a Socratic discussion with your instructor, the goal is for these questions to reinforce your recall and use of general circuit principles and also challenge your ability to integrate multiple symptoms into a sensible explanation of what's wrong in a circuit. Your instructor may also pose additional questions based on those assigned, in order to further challenge and sharpen your diagnostic abilities.

As always, your goal is to fully *explain* your analysis of each problem. Simply obtaining a correct answer is not good enough – you must also demonstrate sound reasoning in order to successfully complete the assignment. Your instructor's responsibility is to probe and challenge your understanding of the relevant principles and analytical processes in order to ensure you have a strong foundation upon which to build further understanding.

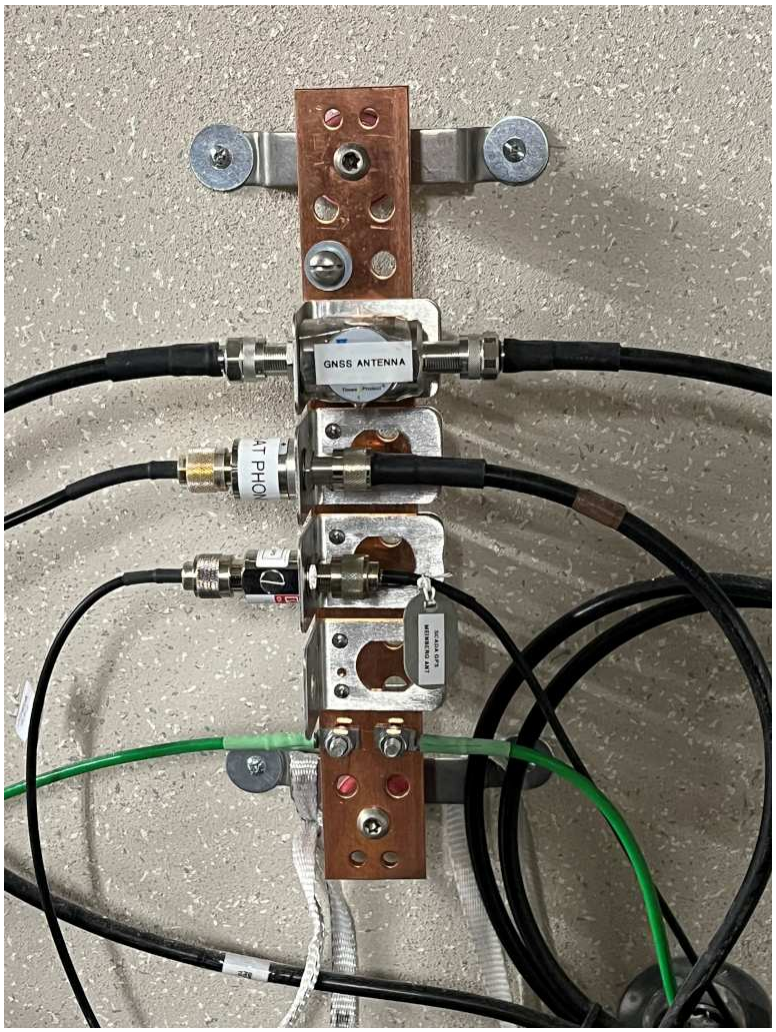
You will note a conspicuous lack of answers given for these diagnostic questions. Unlike standard textbooks where answers to every other question are given somewhere toward the back of the book, here in these learning modules students must rely on other means to check their work. The best way by far is to debate the answers with fellow students and also with the instructor during the Socratic dialogue sessions intended to be used with these learning modules. Reasoning through challenging questions with other people is an excellent tool for developing strong reasoning skills.

Another means of checking your diagnostic answers, where applicable, is to use circuit simulation software to explore the effects of faults placed in circuits. For example, if one of these diagnostic questions requires that you predict the effect of an open or a short in a circuit, you may check the validity of your work by simulating that same fault (substituting a very high resistance in place of that component for an open, and substituting a very low resistance for a short) within software and seeing if the results agree.

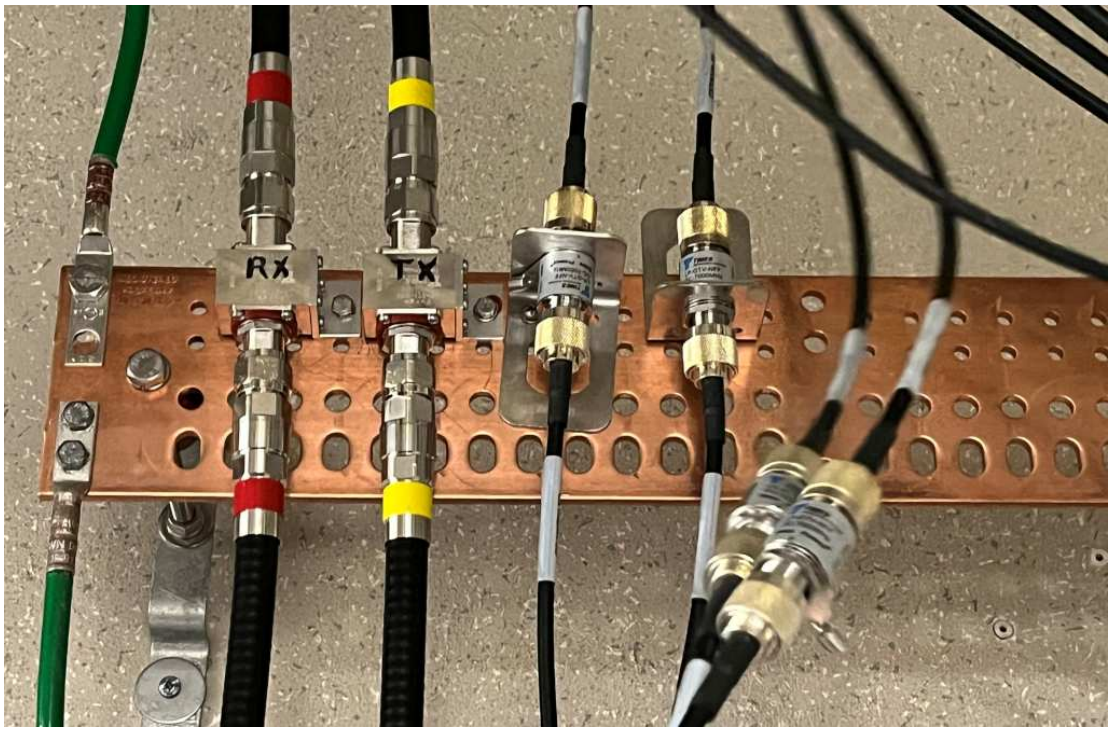
6.3.1 Improperly-installed lightning arrestors

Examine each of these photographs showing lightning arrestors installed on radio-antenna coaxial cabling, and identify any problems you see. Both of these were found in the same facility, both mounted to indoor walls.

Installation #1



Installation #2



Challenges

- Why is flat copper "busbar" material a good choice for a mounting surface for these lightning arrestors?
- How might you go about testing a lightning arrestor for effectiveness?

6.3.2 Partially shorted transformer winding

If a short-circuit develops between two of the turns of wire comprising a transformer winding, what effect does this have on the transformer's ratio?

Challenges

- What operating conditions or environmental factors might lead to a transformer winding failing in this manner?

Appendix A

Problem-Solving Strategies

The ability to solve complex problems is arguably one of the most valuable skills one can possess, and this skill is particularly important in any science-based discipline.

- Study principles, not procedures. Don't be satisfied with merely knowing how to compute solutions – learn *why* those solutions work.
- Identify what it is you need to solve, identify all relevant data, identify all units of measurement, identify any general principles or formulae linking the given information to the solution, and then identify any "missing pieces" to a solution. Annotate all diagrams with this data.
- Sketch a diagram to help visualize the problem. When building a real system, always devise a plan for that system and analyze its function *before* constructing it.
- Follow the units of measurement and meaning of every calculation. If you are ever performing mathematical calculations as part of a problem-solving procedure, and you find yourself unable to apply each and every intermediate result to some aspect of the problem, it means you don't understand what you are doing. Properly done, every mathematical result should have practical meaning for the problem, and not just be an abstract number. You should be able to identify the proper units of measurement for each and every calculated result, and show where that result fits into the problem.
- Perform "thought experiments" to explore the effects of different conditions for theoretical problems. When troubleshooting real systems, perform *diagnostic tests* rather than visually inspecting for faults, the best diagnostic test being the one giving you the most information about the nature and/or location of the fault with the fewest steps.
- Simplify the problem until the solution becomes obvious, and then use that obvious case as a model to follow in solving the more complex version of the problem.
- Check for exceptions to see if your solution is incorrect or incomplete. A good solution will work for *all* known conditions and criteria. A good example of this is the process of testing scientific hypotheses: the task of a scientist is not to find support for a new idea, but rather to *challenge* that new idea to see if it holds up under a battery of tests. The philosophical

principle of *reductio ad absurdum* (i.e. disproving a general idea by finding a specific case where it fails) is useful here.

- Work "backward" from a hypothetical solution to a new set of given conditions.
- Add quantities to problems that are qualitative in nature, because sometimes a little math helps illuminate the scenario.
- Sketch graphs illustrating how variables relate to each other. These may be quantitative (i.e. with realistic number values) or qualitative (i.e. simply showing increases and decreases).
- Treat quantitative problems as qualitative in order to discern the relative magnitudes and/or directions of change of the relevant variables. For example, try determining what happens if a certain variable were to increase or decrease before attempting to precisely calculate quantities: how will each of the dependent variables respond, by increasing, decreasing, or remaining the same as before?
- Consider limiting cases. This works especially well for qualitative problems where you need to determine which direction a variable will change. Take the given condition and magnify that condition to an extreme degree as a way of simplifying the direction of the system's response.
- Check your work. This means regularly testing your conclusions to see if they make sense. This does *not* mean repeating the same steps originally used to obtain the conclusion(s), but rather to use some other means to check validity. Simply repeating procedures often leads to *repeating the same errors* if any were made, which is why alternative paths are better.

Appendix B

Instructional philosophy

B.1 First principles of learning

- **Anyone can learn anything** given appropriate time, effort, resources, challenges, encouragement, and expectations. Dedicating time and investing effort are the student's responsibility; providing resources, challenges, and encouragement are the teacher's responsibility; high expectations are a responsibility shared by both student and teacher.

- **Transfer is not automatic.** The human mind has a natural tendency to compartmentalize information, which means the process of taking knowledge learned in one context and applying it to another usually does not come easy and therefore should never be taken for granted.

- **Learning is iterative.** The human mind rarely learns anything perfectly on the first attempt. Anticipate mistakes and plan for multiple tries to achieve full understanding, using the lessons of those mistakes as feedback to guide future attempts.

- **Information is absorbed, but understanding is created.** Facts and procedures may be memorized easily enough by repeated exposure, but the ability to reliably apply principles to novel scenarios only comes through intense personal effort. This effort is fundamentally creative in nature: casting new concepts in one's own words, running mental experiments to perceive patterns and trends, etc. These acts of making knowledge "one's own" need not be perfect in order to be effective, as the value lies in the activity and not necessarily the finished product. Depth of understanding and permanence of memory are both directly related to mental effort during the learning process – i.e. *easy learning is shallow and fleeting.*

- **Education trumps training.** There is no such thing as an entirely isolated subject, as all fields of knowledge are connected. Training is narrowly-focused and task-oriented. Education is broad-based and principle-oriented. When preparing for a life-long technical career, education beats training every time.

- **Character matters.** Poor habits are more destructive than deficits of knowledge or skill. This is especially true in collective endeavors, where a team's ability to function depends on trust between its members. Simply put, no one wants an untrustworthy person on their team. An essential component of education then, is character development.

- **People learn to be responsible by bearing responsibility.** An irresponsible person is someone who has never *had* to be responsible for anything that mattered enough to them. Just as anyone can learn anything, anyone can become responsible if the personal cost of irresponsibility becomes high enough.

- **What gets measured, gets done.** Accurate and relevant assessment of learning is key to ensuring all students learn. Therefore, it is imperative to measure what matters.

- **Failure is nothing to fear.** Every human being fails, and fails in multiple ways at multiple times. Eventual success only happens when we don't stop trying.

B.2 Proven strategies for instructors

- Assume every student is capable of learning anything they desire given the proper conditions. Treat them as capable adults by granting real responsibility and avoiding artificial incentives such as merit or demerit points.
- Create a consistent culture of high expectations across the entire program of study. Demonstrate and encourage patience, persistence, and a healthy sense of self-skepticism. Anticipate and de-stigmatize error. Teach respect for the capabilities of others as well as respect for one's own fallibility.
- Replace lecture with "inverted" instruction, where students first encounter new concepts through reading and then spend class time in Socratic dialogue with the instructor exploring those concepts and solving problems individually. There is a world of difference between observing someone solve a problem versus actually solving a problem yourself, and so the point of this form of instruction is to place students in a position where they *cannot* passively observe.
- Require students to read extensively, write about what they learn, and dialogue with you and their peers to sharpen their understanding. Apply Francis Bacon's advice that "reading maketh a full man; conference a ready man; and writing an exact man". These are complementary activities helping students expand their confidence and abilities.
- Use artificial intelligence (AI) to challenge student understanding rather than merely provide information. Find productive ways for AI to critique students' clarity of thought and of expression, for example by employing AI as a Socratic-style interlocutor or as a reviewer of students' journals. Properly applied, AI has the ability to expand student access to critical review well outside the bounds of their instructor's reach.
- Build frequent and rapid feedback into the learning process so that students know at all times how well they are learning, to identify problems early and fix them before they grow. Model the intellectual habit of self-assessing and self-correcting your own understanding (i.e. a cognitive *feedback loop*), encouraging students to do the same.
- Use "mastery" as the standard for every assessment, which means the exam or experiment or project must be done with 100% competence in order to pass. Provide students with multiple opportunity for re-tries (different versions of the assessment every time).
- Require students to devise their own hypotheses and procedures on all experiments, so that the process is truly a scientific one. Have students assess their proposed experimental procedures for risk and devise mitigations for those risks. Let nothing be pre-designed about students' experiments other than a stated task (i.e. what principle the experiment shall test) at the start and a set of demonstrable knowledge and skill objectives at the end.
- Have students build as much of their lab equipment as possible: building power sources, building test assemblies[1], and building complete working systems (no kits!). In order to provide

[1] In the program I teach, every student builds their own "Development Board" consisting of a metal chassis with DIN rail, terminal blocks, and an AC-DC power supply of their own making which functions as a portable lab environment they can use at school as well as take home.

this same "ground-up" experience for every new student, this means either previous students take their creations with them, or the systems get disassembled in preparation for the new students, or the systems grow and evolve with each new student group.

- Incorporate external accountability for you and for your students, continuously improving the curriculum and your instructional methods based on proven results. Have students regularly network with active professionals through participation in advisory committee meetings, service projects, tours, jobshadows, internships, etc. Practical suggestions include requiring students to design and build projects for external clients (e.g. community groups, businesses, different departments within the institution), and also requiring students attend all technical advisory committee meetings and to dialogue with the industry representatives at those meetings.
- Repeatedly explore difficult-to-learn concepts across multiple courses, so that students have multiple opportunities to build their understanding.
- Relate all new concepts, whenever possible, to previous concepts and to relevant physical laws. Challenge each and every student, every day, to *reason* from concept to concept and to explain the logical connections between. Challenge students to verify their conclusions by multiple approaches (e.g. double-checking their work using different methods). Ask *"Why?"* often.
- Maintain detailed records on each student's performance and share these records privately with them. These records should include academic performance as well as professionally relevant behavioral tendencies.
- Hold mandatory "check-in" meetings between all program faculty and each new student during their first term. Offer these to all other students as an option, except for any students continuing to manifest unprofessional behaviors, poor academic performance, or who have some other need for a face-to-face meeting with faculty.
- Address problems while they are small, before they grow larger. This is equally true for tutoring technical concepts as it is for helping students build professional habits.
- Build rigorous quality control into the curriculum to ensure every student masters every important concept, and that the mastery is retained over time. This includes (1) review questions added to every exam to re-assess knowledge taught in previous terms, (2) cumulative exams at the end of every term to re-assess all important concepts back to the very beginning of the program, and (3) review assessments in practical (hands-on) coursework to ensure critically-important skills were indeed taught and are still retained. What you will find by doing this is that it actually boosts retention of students by ensuring that important knowledge gets taught and is retained over long spans of time. In the absence of such quality control, student learning and retention tends to be spotty and this contributes to drop-out and failure rates later in their education.
- Finally, *never rush learning.* Education is not a race. Give your students ample time to digest complex ideas, as you continually remind yourself of just how long it took you to achieve mastery! Long-term retention and the consistently correct application of concepts are always the result of *focused effort over long periods of time* which means there are no shortcuts to learning.

B.3 Proven strategies for students

The single most important piece of advice I have for any student of any subject is to take responsibility for your own development in all areas of life including mental development. Expecting others in your life to entirely guide your own development is a recipe for disappointment. This is just as true for students enrolled in formal learning institutions as it is for auto-didacts pursuing learning entirely on their own. Learning to think in new ways is key to being able to gainfully use information, to make informed decisions about your life, and to best serve those you care about. With this in mind, I offer the following advice to students:

- **Approach all learning as valuable**. No matter what course you take, no matter who you learn from, no matter the subject, there is something useful in every learning experience. If you don't see the value of every new experience, you are not looking closely enough!
- **Continually challenge yourself**. Let other people take shortcuts and find easy answers to easy problems. The purpose of education is to stretch your mind, in order to shape it into a more powerful tool. This doesn't come by taking the path of least resistance. An excellent analogy for an empowering education is productive physical exercise: becoming stronger, more flexible, and more persistent only comes through intense personal effort.
- **Master the use of language**. This includes reading extensively, writing every day, listening closely, and speaking articulately. To a great extent language channels and empowers thought, so the better you are at wielding language the better you will be at grasping abstract concepts and articulating them not only for your benefit but for others as well.
- **Do not limit yourself to the resources given to you**. Read books that are not on the reading list. Run experiments that aren't assigned to you. Form study groups outside of class. Take an entrepreneurial approach to your own education, as though it were a business you were building for your future benefit.
- **Express and share what you learn**. Take every opportunity to teach what you have learned to others, as this will not only help them but will also strengthen your own understanding[2].
- Realize that **no one can give you understanding**, just as no one can give you physical fitness. These both must be *built*.
- **Above all, recognize that learning is hard work, and that a certain level of frustration is unavoidable**. There are times when you will struggle to grasp some of these concepts, and that struggle is a natural thing. Take heart that it will yield with persistent and varied[3] effort, and never give up! That concepts don't immediately come to you is not a sign of something wrong, but rather of something right: that you have found a worthy challenge!

[2] On a personal note, I was surprised to learn just how much my own understanding of electronics and related subjects was strengthened by becoming a teacher. When you are tasked every day with helping other people grasp complex topics, it catalyzes your own learning by giving you powerful incentives to study, to articulate your thoughts, and to reflect deeply on the process of learning.

[3] As the old saying goes, "Insanity is trying the same thing over and over again, expecting different results." If you find yourself stumped by something in the text, you should attempt a different approach. Alter the thought experiment, change the mathematical parameters, do whatever you can to see the problem in a slightly different light, and then the solution will often present itself more readily.

B.4 Design of these learning modules

"The unexamined circuit is not worth energizing" – Socrates (if he had taught electricity)

These learning modules, although useful for self-study, were designed to be used in a formal learning environment where a subject-matter expert challenges students to digest the content and exercise their critical thinking abilities in the answering of questions and in the construction and testing of working circuits. Every effort has been made to embed the following instructional and assessment philosophies within:

- The first goal of education is to enhance clear and independent thought, in order that every student reach their fullest potential in a highly complex and inter-dependent world. Robust reasoning is *always* more important than particulars of any subject matter, because its application is universal.
- Literacy is fundamental to independent learning and thought because text continues to be the most efficient way to communicate complex ideas over space and time. Those who cannot read with ease are limited in their ability to acquire knowledge and perspective.
- Articulate communication is fundamental to work that is complex and interdisciplinary.
- Faulty assumptions and poor reasoning are best corrected through challenge, not presentation. The rhetorical technique of *reductio ad absurdum* (disproving an assertion by exposing an absurdity) works well to discipline student's minds, not only to correct the problem at hand but also to learn how to detect and correct future errors.
- Important principles should be repeatedly explored and widely applied throughout a course of study, not only to reinforce their importance and help ensure their mastery, but also to showcase the interconnectedness and utility of knowledge.

These learning modules were expressly designed to be used in an "inverted" teaching environment[4] where students first read the introductory and tutorial chapters on their own, then individually attempt to answer the questions and construct working circuits according to the experiment and project guidelines. The instructor never lectures, but instead meets regularly with each individual student to review their progress, answer questions, identify misconceptions, and challenge the student to new depths of understanding through further questioning. Regular meetings between instructor and student should resemble a Socratic[5] dialogue, where questions serve as scalpels to dissect topics and expose assumptions. The student passes each module only after consistently demonstrating their ability to logically analyze and correctly apply all major concepts in each question or project/experiment. The instructor must be vigilant in probing each student's understanding to ensure they are truly *reasoning* and not just *memorizing*. This is why "Challenge" points appear throughout, as prompts for students to think deeper about topics and as starting points for instructor queries. Sometimes these challenge points require additional knowledge that hasn't been covered in the series to answer in full. This is okay, as the major purpose of the Challenges is to stimulate analysis and synthesis on the part of each student.

The instructor must possess enough mastery of the subject matter and awareness of students' reasoning to generate their own follow-up questions to practically any student response. Even completely correct answers given by the student should be challenged by the instructor for the purpose of having students practice articulating their thoughts and defending their reasoning. Conceptual errors committed by the student should be exposed and corrected not by direct instruction, but rather by reducing the errors to an absurdity[6] through well-chosen questions and thought experiments posed by the instructor. Becoming proficient at this style of instruction requires time and dedication, but the positive effects on critical thinking for both student and instructor are spectacular.

An inspection of these learning modules reveals certain unique characteristics. One of these is a bias toward thorough explanations in the tutorial chapters. Without a live instructor to explain concepts and applications to students, the text itself must fulfill this role. This philosophy results in lengthier explanations than what you might typically find in a textbook, each step of the reasoning process fully explained, including footnotes addressing common questions and concerns students raise while learning these concepts. Each tutorial seeks to not only explain each major concept in sufficient detail, but also to explain the logic of each concept and how each may be developed

[4] In a traditional teaching environment, students first encounter new information via *lecture* from an expert, and then independently apply that information via *homework*. In an "inverted" course of study, students first encounter new information via *homework*, and then independently apply that information under the scrutiny of an expert. The expert's role in lecture is to simply *explain*, but the expert's role in an inverted session is to *challenge*, *critique*, and if necessary *explain* where gaps in understanding still exist.

[5] Socrates is a figure in ancient Greek philosophy famous for his unflinching style of questioning. Although he authored no texts, he appears as a character in Plato's many writings. The essence of Socratic philosophy is to leave no question unexamined and no point of view unchallenged. While purists may argue a topic such as electric circuits is too narrow for a true Socratic-style dialogue, I would argue that the essential thought processes involved with scientific reasoning on *any* topic are not far removed from the Socratic ideal, and that students of electricity and electronics would do very well to challenge assumptions, pose thought experiments, identify fallacies, and otherwise employ the arsenal of critical thinking skills modeled by Socrates.

[6] This rhetorical technique is known by the Latin phrase *reductio ad absurdum*. The concept is to expose errors by counter-example, since only one solid counter-example is necessary to disprove a universal claim. As an example of this, consider the common misconception among beginning students of electricity that voltage cannot exist without current. One way to apply *reductio ad absurdum* to this statement is to ask how much current passes through a fully-charged battery connected to nothing (i.e. a clear example of voltage existing without current).

from "first principles". Again, this reflects the goal of developing clear and independent thought in students' minds, by showing how clear and logical thought was used to forge each concept. Students benefit from witnessing a model of clear thinking in action, and these tutorials strive to be just that.

Another feature of these learning modules is that they do not treat topics in isolation. Rather, important concepts are introduced early in the series, and appear repeatedly as stepping-stones toward other concepts in subsequent modules. This helps to avoid the "compartmentalization" of knowledge, demonstrating the inter-connectedness of concepts and simultaneously reinforcing them. Each module is fairly complete in itself, reserving the beginning of its tutorial to a review of foundational concepts.

To high standards of education,

Tony R. Kuphaldt

Appendix C

Tools used

I am indebted to the developers of many open-source software applications in the creation of these learning modules. The following is a list of these applications with some commentary on each.

You will notice a theme common to many of these applications: a bias toward *code*. Although I am by no means an expert programmer in any computer language, I understand and appreciate the flexibility offered by code-based applications where the user (you) enters commands into a plain ASCII text file, which the software then reads and processes to create the final output. Code-based computer applications are by their very nature *extensible*, while WYSIWYG (What You See Is What You Get) applications are generally limited to whatever user interface the developer makes for you.

The `GNU/Linux` computer operating system

> There is so much to be said about Linus Torvalds' `Linux` and Richard Stallman's `GNU` project. First, to credit just these two individuals is to fail to do justice to the *mob* of passionate volunteers who contributed to make this amazing software a reality. I first learned of `Linux` back in 1996, and have been using this operating system on my personal computers almost exclusively since then. It is *free*, it is completely *configurable*, and it permits the continued use of highly efficient `Unix` applications and scripting languages (e.g. shell scripts, Makefiles, `sed`, `awk`) developed over many decades. `Linux` not only provided me with a powerful computing platform, but its open design served to inspire my life's work of creating open-source educational resources.

Bram Moolenaar's `Vim` text editor

> Writing code for any code-based computer application requires a *text editor*, which may be thought of as a word processor strictly limited to outputting plain-ASCII text files. Many good text editors exist, and one's choice of text editor seems to be a deeply personal matter within the programming world. I prefer `Vim` because it operates very similarly to `vi` which is ubiquitous on `Unix`/`Linux` operating systems, and because it may be entirely operated via keyboard (i.e. no mouse required) which makes it fast to use.

Donald Knuth's TEX typesetting system

Developed in the late 1970's and early 1980's by computer scientist extraordinaire Donald Knuth to typeset his multi-volume magnum opus *The Art of Computer Programming*, this software allows the production of formatted text for screen-viewing or paper printing, all by writing plain-text code to describe how the formatted text is supposed to appear. TEX is not just a markup language for documents, but it is also a Turing-complete programming language in and of itself, allowing useful algorithms to be created to control the production of documents. Simply put, TEX *is a programmer's approach to word processing*. Since TEX is controlled by code written in a plain-text file, this means anyone may read that plain-text file to see exactly how the document was created. This openness afforded by the code-based nature of TEX makes it relatively easy to learn how other people have created their own TEX documents. By contrast, examining a beautiful document created in a conventional WYSIWYG word processor such as Microsoft `Word` suggests nothing to the reader about *how* that document was created, or what the user might do to create something similar. As Mr. Knuth himself once quipped, conventional word processing applications should be called WYSIAYG (What You See Is *All* You Get).

Leslie Lamport's LATEX extensions to TEX

Like all true programming languages, TEX is inherently extensible. So, years after the release of TEX to the public, Leslie Lamport decided to create a massive extension allowing easier compilation of book-length documents. The result was LATEX, which is the markup language used to create all ModEL module documents. You could say that TEX is to LATEX as `C` is to `C++`. This means it is permissible to use any and all TEX commands within LATEX source code, and it all still works. Some of the features offered by LATEX that would be challenging to implement in TEX include automatic index and table-of-content creation.

Tim Edwards' `Xcircuit` drafting program

This wonderful program is what I use to create all the schematic diagrams and illustrations (but not photographic images or mathematical plots) throughout the ModEL project. It natively outputs PostScript format which is a true vector graphic format (this is why the images do not pixellate when you zoom in for a closer view), and it is so simple to use that I have never had to read the manual! Object libraries are easy to create for `Xcircuit`, being plain-text files using PostScript programming conventions. Over the years I have collected a large set of object libraries useful for drawing electrical and electronic schematics, pictorial diagrams, and other technical illustrations.

`Gimp` graphic image manipulation program

Essentially an open-source clone of Adobe's `PhotoShop`, I use `Gimp` to resize, crop, and convert file formats for all of the photographic images appearing in the ModEL modules. Although `Gimp` does offer its own scripting language (called `Script-Fu`), I have never had occasion to use it. Thus, my utilization of `Gimp` to merely crop, resize, and convert graphic images is akin to using a sword to slice bread.

`SPICE` circuit simulation program

`SPICE` is to circuit analysis as TEX is to document creation: it is a form of markup language designed to describe a certain object to be processed in plain-ASCII text. When the plain-text "source file" is compiled by the software, it outputs the final result. More modern circuit analysis tools certainly exist, but I prefer `SPICE` for the following reasons: it is *free*, it is *fast*, it is *reliable*, and it is a fantastic tool for *teaching* students of electricity and electronics how to write simple code. I happen to use rather old versions of `SPICE`, version 2g6 being my "go to" application when I only require text-based output. `NGSPICE` (version 26), which is based on Berkeley `SPICE` version 3f5, is used when I require graphical output for such things as time-domain waveforms and Bode plots. In all `SPICE` example netlists I strive to use coding conventions compatible with all `SPICE` versions.

Andrew D. Hwang's `ePiX` mathematical visualization programming library

This amazing project is a `C++` library you may link to any `C/C++` code for the purpose of generating PostScript graphic images of mathematical functions. As a completely free and open-source project, it does all the plotting I would otherwise use a Computer Algebra System (CAS) such as `Mathematica` or `Maple` to do. It should be said that `ePiX` is *not* a Computer Algebra System like `Mathematica` or `Maple`, but merely a mathematical *visualization* tool. In other words, it won't determine integrals for you (you'll have to implement that in your own `C/C++` code!), but it can graph the results, and it does so beautifully. What I really admire about `ePiX` is that it is a `C++` programming library, which means it builds on the existing power and toolset available with that programming language. Mr. Hwang could have probably developed his own stand-alone application for mathematical plotting, but by creating a `C++` library to do the same thing he accomplished something much greater.

`gnuplot` mathematical visualization software

Another open-source tool for mathematical visualization is `gnuplot`. Interestingly, this tool is *not* part of Richard Stallman's GNU project, its name being a coincidence. For this reason the authors prefer "gnu" *not* be capitalized at all to avoid confusion. This is a much "lighter-weight" alternative to a spreadsheet for plotting tabular data, and the fact that it easily outputs directly to an X11 console or a file in a number of different graphical formats (including PostScript) is very helpful. I typically set my `gnuplot` output format to default (X11 on my Linux PC) for quick viewing while I'm developing a visualization, then switch to PostScript file export once the visual is ready to include in the document(s) I'm writing. As with my use of `Gimp` to do rudimentary image editing, my use of `gnuplot` only scratches the surface of its capabilities, but the important points are that it's *free* and that it *works well*.

`Python` programming language

Both Python and C++ find extensive use in these modules as instructional aids and exercises, but I'm listing Python here as a *tool* for myself because I use it almost daily as a *calculator*. If you open a Python interpreter console and type `from math import *` you can type mathematical expressions and have it return results just as you would on a hand calculator. Complex-number (i.e. *phasor*) arithmetic is similarly supported if you include the complex-math library (`from cmath import *`). Examples of this are shown in the Programming References chapter (if included) in each module. Of course, being a fully-featured programming language, Python also supports conditionals, loops, and other structures useful for calculation of quantities. Also, running in a console environment where all entries and returned values show as text in a chronologically-ordered list makes it easy to copy-and-paste those calculations to document exactly how they were performed.

Appendix D

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Appendix E

References

Antenna Systems, AF manual 52-19, United States Air Force, June 1953.

The ARRL Antenna Book, Eleventh Edition, The American Radio Relay League, Inc., Newington, CT, 1968.

The ARRL Handbook For Radio Amateurs, 2001 Edition, ARRL – the national association for Amateur Radio, Newington, CT, 2001.

"Coaxial Cable Protection" white paper, document 1485-005, Infinite Electronics Incorporated, 2017.

"Earth Ground Measurements" technical note, document 1485-008RevA, Infinite Electronics Incorporated, 2017.

McCoy, Lewis G. (W1ICP), "The Ultimate Transmatch", pages 24-27 and 58, QST magazine, July 1970.

Salas, Phil (AD5X), "A 100-Watt Compact Z-Match Antenna Tuner".

Shrader, Robert L., *Electronic Communication*, Fourth Edition, McGraw-Hill Incorporated, Gregg Division, New York, NY, 1980.

"Smartuners for Stealth Antennas", SGC Incorporated, Bellevue, WA, 1997.

Smith, W. W., *The "Radio" Handbook*, Sixth Edition, Radio Ltd., Santa Barbara, CA, 1939.

Appendix F

Version history

This is a list showing all significant additions, corrections, and other edits made to this learning module. Each entry is referenced by calendar date in reverse chronological order (newest version first), which appears on the front cover of every learning module for easy reference. Any contributors to this open-source document are listed here as well.

21 August 2026 – added some Diagnostic Questions regarding improper lightning arrestor installations, with photographs!

8 October 2025 – minor edits to the Tutorial, including the addition of a photograph showing ground straps at a radio installation and also many index entries.

30 June 2025 – added new content to the Tutorial chapter discussing different types of baluns, as well as a new section on ununs, and moved the "Surge suppression" section to an earlier place in the Tutorial. Also created a new section of the Tutorial for the introductory text.

27 June 2025 – added a new Technical Reference section on common coaxial cable types.

26 March 2025 – added some content to the Tutorial discussing Delta and Gamma match systems for dipole antennas. Also edited the text to avoid assumptions that resonance is always the goal for antenna operations.

6 March 2025 – edited the "Matching section calculator program" Quantitative Reasoning question to have the students' code include calculation of matching section length.

9 November 2024 – edited one of the "Challenging concepts" listed in the Introduction chapter, single-ended versus differential voltage signals.

22 October 2024 – added a new Case Tutorial section with example decibel calculations for RF cable losses.

30 September 2024 – divided the Introduction chapter into sections, one with recommendations for students, one with a listing of challenging concepts, and one with recommendations for instructors.

Also added Technical Reference sections on the Poynting vector and Maxwell's equations.

19 March 2024 – added comments in the "Antenna impedance matching" section about the need to have whole-number winding turns for any transformer.

16 October 2023 – edited image_4598 to show the 1/4-wavelength matching section having different conductor spacing to give it a different characteristic impedance than the transmission line.

4 June 2023 – added a Quantitative Reasoning question challenging students to complete a computer program written in C to convert between wavelength and frequency.

28 November 2022 – placed questions at the top of the itemized list in the Introduction chapter prompting students to devise experiments related to the tutorial content.

21 March 2022 – minor clarification on the value of a suitable "dummy" load resistor for transmitter testing.

10 March 2022 – added content to the Introduction chapter.

7 January 2022 – added some comments about the effect of a monopole antenna's counterpoise array affecting its input impedance.

29 December 2021 – eliminated some redundant wording in the Tutorial.

26 October 2021 – added text and a photograph regarding the use of dummy loads to simulate an antenna.

13 May 2021 – expanded comments related to SWR in the Tutorial.

10 May 2021 – commented out or deleted empty chapters.

8 May 2021 – added animations showing how a standing waves are created by the constructive and destructive interference of forward and reflected waves along a transmission line.

4 May 2021 – added comments to the Tutorial about the importance of monopole antenna grounding and counterpoises.

19-23 April 2021 – minor edits to the Tutorial (especially image_4594 and image_4606), and also added content to the Introduction chapter. Also eliminated the Full Tutorial and made the Simplified Tutorial the only Tutorial.

4 April 2021 – added section to the Tutorial on surge suppression, and corrected some mis-spelled words.

30 November 2020 – minor edits to the Tutorial.

28 November 2020 – added Technical Reference on LC impedance-transformation networks.

1 November 2020 – added content to the Simplified Tutorial chapter.

28 October 2020 – document first created.

Index

Adding quantities to a qualitative problem, 280
Ampère's Circuital Law, 71
Ampère, André-Marie, 71
Annotating diagrams, 279
Antenna, 15, 73
Antenna coupling network, 24
Antenna matching network, 24
Antenna matching section, 25
Antenna model, lumped-parameter, 26
Anti-node, 21
Arrestor, lightning, 31
Autotransformer, 37

Balanced system, 36
Balun, 37
Balun, choking, 39
Balun, current, 39
Balun, voltage, 39
Bel, 42

CB radio, 17, 23
Characteristic impedance, 16
Checking for exceptions, 280
Checking your work, 280
Choking balun, 39
Citizen's Band radio, 17, 23
Coaxial feedline, 18
Code, computer, 289
Common logarithm, 42
Conservation of Energy, 55, 67
Counterpoise, 36
Cross product, 66
Current balun, 39

dB, 42
dBm, 46
dBW, 47
Decibel, 42
Delta match, 26
Dimensional analysis, 279
Dissipation, 15
Dummy load, 17

Edwards, Tim, 290
Electromagnetic wave, 69

Faraday's Law of electromagnetic induction, 71
Faraday, Michael, 71
Feedline, coaxial, 18
Feedline, ladder, 18
Feedline, twin-lead, 18
Ferrite, 38
Filter, 33
Flat transmission line, 21
Forward power, 20
Forward waveform, 76, 166
Fourier transform, 48

Gain, amplifier, 42
Gamma match, 28
Gas discharge tube, 32
Gauss's Law of electric fields, 70
Gauss's Law of magnetic fields, 70
Graph values to solve a problem, 280
Greenleaf, Cynthia, 257
Ground plane, 36

Heaviside, Oliver, 70
Hertz, Heinrich, 72
How to teach with these modules, 287
Hwang, Andrew D., 291

Identify given data, 279
Identify relevant principles, 279
Impedance, 52

Impedance, characteristic, 16
Impedance, surge, 16
Incident waveform, 76, 166
Induction coil, 73
Intermediate results, 279
Inverted instruction, 287

Joule's Law, 49, 66

Knuth, Donald, 290

Ladder feedline, 18
Lamport, Leslie, 290
Laplace transform, 48
Lightning arrestor, 31
Limiting cases, 280
Load, 15
Load, dummy, 17
Logarithm, common, 42
Lumped-parameter model for antenna, 26

Magnetically soft material, 38
Matching stubs, 27
Maximum Power Transfer Theorem, 55
Maximum power transfer theorem, 16
Maxwell's electromagnetic equations, 70
Maxwell, James Clerk, 70
Metacognition, 262
Monopole, 70
Moolenaar, Bram, 289
Murphy, Lynn, 257

Narrowband, 28
Node, 21

Ohm's Law, 15
Open-source, 289

Power factor, 22
Poynting, John H., 66
Problem-solving: annotate diagrams, 279
Problem-solving: check for exceptions, 280
Problem-solving: checking work, 280
Problem-solving: dimensional analysis, 279
Problem-solving: graph values, 280
Problem-solving: identify given data, 279
Problem-solving: identify relevant principles, 279
Problem-solving: interpret intermediate results, 279
Problem-solving: limiting cases, 280
Problem-solving: qualitative to quantitative, 280
Problem-solving: quantitative to qualitative, 280
Problem-solving: reductio ad absurdum, 280
Problem-solving: simplify the system, 279
Problem-solving: thought experiment, 279
Problem-solving: track units of measurement, 279
Problem-solving: visually represent the system, 279
Problem-solving: work in reverse, 280

Qualitatively approaching a quantitative problem, 280

Radiation resistance, 15
Radiator, 72, 73
Reactance, 15, 52
Reading Apprenticeship, 257
Reductio ad absurdum, 280, 286, 287
Reflected power, 20
Reflected signals, 16
Reflected waveform, 76, 166
Resonator, 72, 73
Right-hand rule, 66

Schoenbach, Ruth, 257
Scientific method, 262
Signal reflection, 16
Simplifying a system, 279
Skin effect, 34, 40
Socrates, 286
Socratic dialogue, 287
Soft ferrite, 38
Soft magnetic material, 38
Source, 15
SPICE, 257
Stallman, Richard, 289
Standing wave, 20, 76, 166
Standing Wave Ratio, 21, 76, 166
Stub matching networks, 27
Surge impedance, 16
SWR, 21, 76, 166
SWR meter, 23

Thévenin's theorem, 16
Thought experiment, 22, 279
Torvalds, Linus, 289
Transform function, 48
Transformer, 24
Transmission line, 16
Twin-lead feedline, 18

Unbalanced system, 36
Units of measurement, 279
Unun, 40

Vector cross-product, 66
Visualizing a system, 279
Voltage balun, 39

Waveguide, 20
Wideband, 28
Work in reverse to solve a problem, 280
WYSIWYG, 289, 290