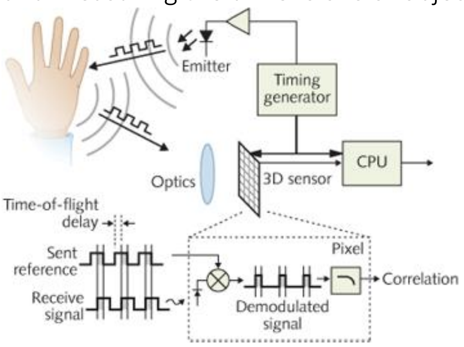
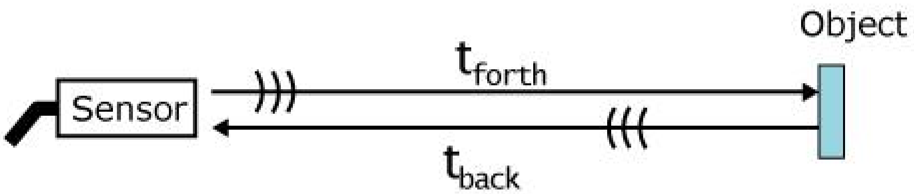
9. Time of flight Displacement Sensing

Position tracking devices are used to measure the change in an object's position and orientation over time. Time of flight -based distance measurement often serves as a way of positioning parts, navigating automated vehicles like stacker cranes, and measuring the dimensions of objects like boxes.





Time-of-Flight principle (ToF) is a method for measuring the distance between a sensor and an object, based on the time difference between the emission of a signal and its return to the sensor, after being reflected by an object. The parameters required to calculate range are simply the speed of sound in air (343.2 metres per second) or the speed of light(299792458 metres per second). Time-of-flight (TOF) systems may be of the "round-trip" (i.e., echo, reflection) type or the "one-way" (i.e., cooperative target, active target) type.

- Round-trip systems effectively measure the time taken for an emitted energy pattern to travel from a reference source to a partially reflective target and back again. The advantages of TOF systems arise from the direct nature of their straight-line active sensing. The returned signal follows essentially the same path back to a receiver located in close proximity to the transmitter. The absolute range to an observed point is directly available as output with no complicated analysis requirements.
- One-way systems transmit a signal at the reference end and receive it at the target end or vice versa. Some form of synchronizing reference must be available to both ends in order to establish the time of flight.

In TOF methods, the distance comes from measuring the time it takes the signal to travel the distance between the target and the detector. In a typical direct TOF setup, a clock measures this time, while in an indirect TOF setup, the time is inferred from, for example, the phase relationship between intensity-modulated emitted and detected wave. Another version of indirect TOF, uses short (tens of ns) pulses; the distance again comes from phase comparison between the emitted and received pulses.

A characteristic of many TOF systems is that their range resolution capability is based solely on the shortest time interval they can resolve, and not the absolute range being measured. That is, whether an object is near or far, the error on the measurement is basically constant. The distance to the target is extracted from the measured phase shift of the reflected waves. Two problems associated with such sensors are:

- difficulty in measuring short distances (which requires a very high modulation frequency), and
- the need for a mechanical scanning/switching system to get additional information (such as orientation)

9.1 Types of waves

The time of flight sensing systems are contactless position sensors as their name suggests. All noncontact, active ranging devices employ some form of energy. They are based on the principles that energy propagates at a known, finite, speed (e.g., the speed of light, the speed of sound in air).Therefore, various types of signals (also called carriers) can be used with ToF, the most common being sound and light. Depending on whether radio frequencies, light frequencies, or sound energy is used, these devices go by names such as radar, lidar, and sonar.

Sound: Ranging systems based on sound energy are usually of the pulsed-echo TOF type and employ carrier frequencies in the so-called "ultrasonic" (beyond audible) range of frequencies. Besides being inaudible, ultrasonic frequencies are more readily focused into directed beams and are practical to generate and detect using piezoelectric transducers.

Ultrasonic signals propagate through air, but long distance transmission is much more effective in liquids, like water. Ultrasonic ranging techniques(or SONAR, for SOund Navigation and Ranging) were first developed for subsea application.

The frequencies typically used in sonic ranging applications are at a few tens of kilohertz to a few hundred kilohertz. A basic trade-off in the choice of ultrasonic frequency is that while high frequencies can be shaped into narrower beams, and therefore achieve higher lateral resolution, they tend to fade more quickly with distance.

When comparing sound energy to electromagnetic energy for TOF-based techniques, one needs to remember that sound, unlike light, propagates at not only much lower speeds, but with considerably more speed variation, depending on the type and state of the carrying media. Therefore, factors like air humidity and pressure will affect the accuracy of a TOF ranging device.

Radio Frequency: Echo-type TOF ranging systems based on the band of the electromagnetic spectrum between approximately 1 m and 1 mm wavelength are known as RADAR (Radio Detection And Ranging). Radio waves can be used for long-distance detection in a variety of atmospheric conditions.

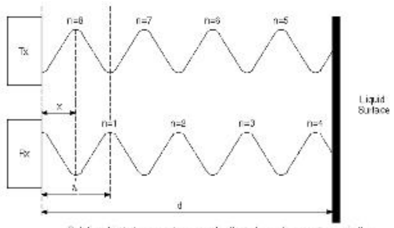
As in the case of sound waves, there are trade-offs to be addressed in the choice of frequency. Long waves tend to propagate better over long distances, but short waves can be focused into narrow beams capable of better lateral discrimination.

An example of a TOF one-way (active receiver) system that uses radio frequencies is the global positioning system (GPS). The distance between a receiver on land is determined by each of several orbiting satellites equipped with a transmitter and a very precise Cesium clock for synchronization.

Light: Beyond the radio portion of the electromagnetic spectrum are the infrared, visible, and ultraviolet frequencies. These frequencies can be produced by lasers and detected by solid-state photosensitive devices and are useful for both TOF and active triangulation ranging.

Measurements

Phase-Shift Measurement: A small portion of the wave (potentially up to six orders of magnitude less in amplitude) is reflected by the target's surface back to the detector along a direct path. The returned energy is compared to a simultaneously generated reference that has been split off from the original signal, and the relative phase shift between the tow is measured as illustrated below.



Relationship between outgoing and reflected waveforms, where x is the distance corresponding to the differential phase. (Adapted from [Woodbury et al., 1993].)

The relative phase-shift expressed as a function of distance to the reflecting target surface is:

$$\phi = \frac{4\pi d}{\lambda}$$

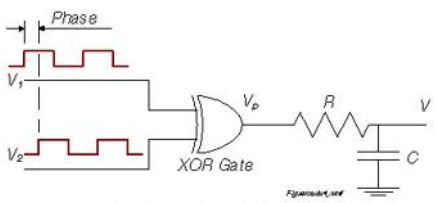
where

ϕ = phase shift

λ = modulation wavelength

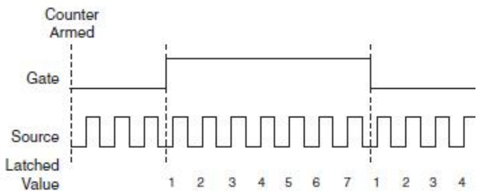
d = distance to target

For square-wave modulation at the relatively low frequencies of ultrasonic systems (20 to 200kHz), the phase difference between incoming and outgoing waveforms can be measured with the simple linear circuit shown below. The output of the *exclusive-or* gate goes high whenever its inputs are at opposite logic levels, generating a voltage across the capacitor that is proportional to the phase-shift.



At low frequencies typical of ultrasonic systems, a simple phase-detection circuit based on an *exclusive-or* gate will generate an analog output voltage proportional to the phase difference seen by the inputs. (Adapted from [Figueroa and Barbieri, 1991].)

Time measurement

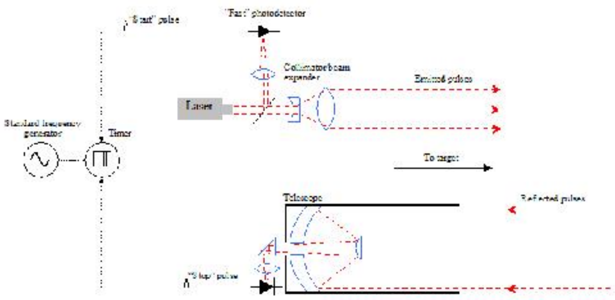


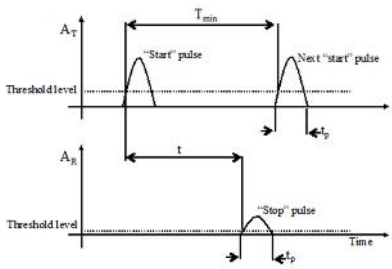
The time measurement can be done by using counters. Counters are excited with oscillators which generates square waves with relatively high frequencies. The counters can be triggered via external pulses. The first trigger to counter makes it start the register the number of pulses incrementally until second trigger comes. The total number of pulses logged in register is multiplied via oscillator period to calculate the total amount of time passed between two triggers.

9.2 Lidar

Echo-type TOF techniques are known as LIDAR (LIght Detection And Ranging), in keeping with the terminology introduced earlier. <u>While light frequencies attenuate more than radio frequencies through cloud and fog, they can have very narrow beam widths, allowing superior lateral resolution and target selectivity.</u>
Light Detection And Ranging (LIDAR) is a classic TOF system (both direct and indirect versions exist) for remote depth sensing. In direct TOF, the time jitter of the clock and of the photodetectors used to control it limit the smallest measurable distance, whereas the strength of the returned light limits the largest distance. In indirect TOF using pulsed illumination, other factors, such us duration of the illumination pulse, limits the minimum and maximum ranges.

Direct time of flight: In the direct TOF techniques, the time of flight is measured directly with a clock.





The laser emits pulses of light of wavelength λ_0, duration t_p, and repetition period T. A beam splitter directs some fraction of the light to a "fast" photodetector such as a PIN photodiode or avalanche photodiode; the output pulse of the photodetector provides the "start" pulse to a timer (clock).

The remaining fraction of light passes through the collimation and beam expander optics and travels to the target in a medium with index of refraction n. After reflection from the target, some fraction of the light is collected by the telescope and directed towards the second "fast" photodetector. The photodetector produces the "stop" pulse to the timer.

$d = \frac{cT_f}{2n}$ ideal case n=1.

The amplitude A_T of the start pulse voltage or current produced by the photodetector is controlled by the amount of light siphoned to the detector by the beam splitter. The amplitude A_R of the stop pulse depends on the amount of reflected light collected by the telescope. For a given telescope aperture size, this quantity of light depends on the light power in the laser pulse, the distance to the target, and the characteristics of the reflection.
As shown in Figure, the repetition period T of the laser pulses should not be smaller than $T_{min} = t + t_p$ or the maximum repetition frequency not be greater than $f_{max} = {}^1/T_{min}$.

For a target 100 m away, t = 0.67 μs. If $t_p << t$, f_{max} = 1.5 MHz. The repetition frequency decreases linearly with increasing d. This has no consequences if the target is stationary, but if it is not, the resolution of its position as a function of time decreases with d.

Phase comparison method (Indirect time of flight)

Figure below illustrates the concept of measuring distance to a target using the phase shift ϕ between the intensity modulated transmitted and received waves. The transmitter emits light whose intensity is modulated (sinusoidal modulation is common) by either the transmitter itself (if it is a laser or LED) or an optical system such a mechanical shutter. The light does not need to be monochromatic and polarized. The light reflects from the target and arrives at the receiver having a phase shift with respect to the transmitted wave of ϕ, which can have a value between 0 and 2π.

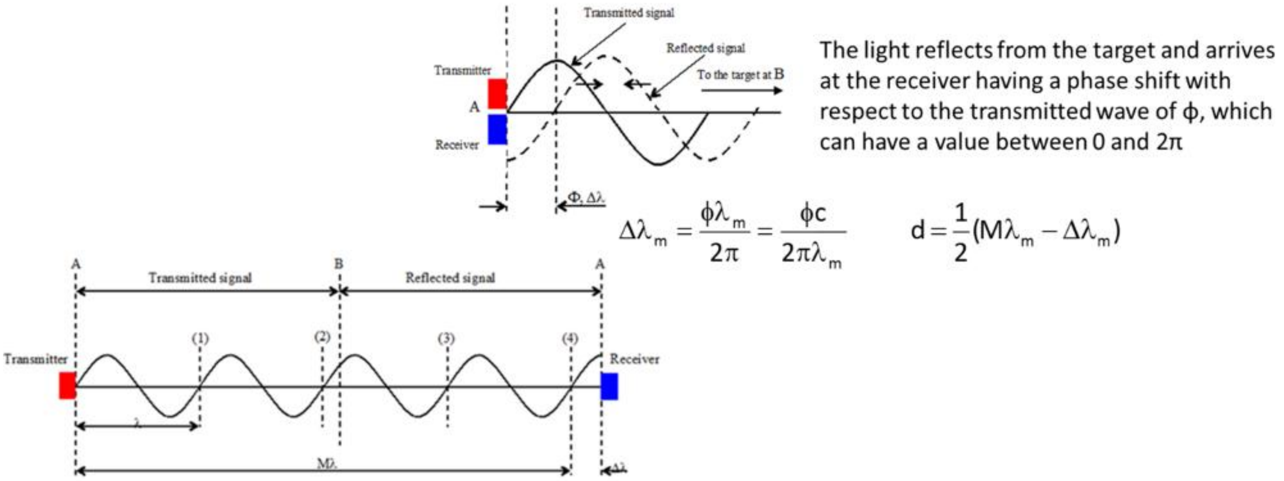


Figure Phase comparison method of measuring distance. The emitted light is intensity-modulated (assumed sinusoidal) with the modulation wavelength λ_m. Adapted from Petrie & Toth (2009).

If the wavelength of the sinusoidal modulation is λ_m, Equations below gives the corresponding phase shift and the distance to the target.

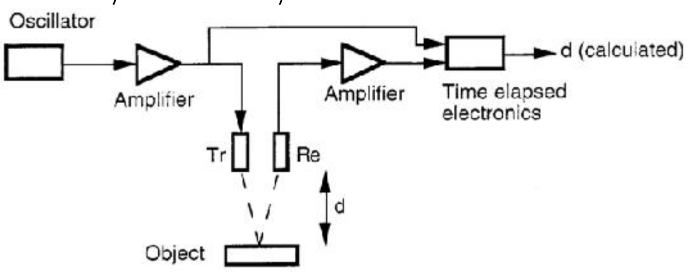
$$\Delta\lambda_m = \frac{\phi\lambda_m}{2\pi} = \frac{\phi c}{2\pi\lambda_m}$$

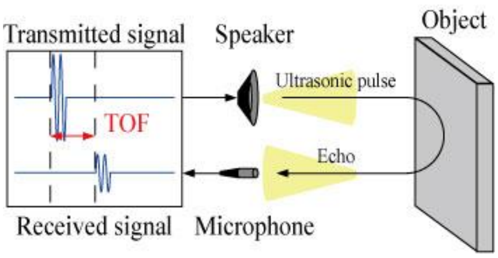
$$d = \frac{1}{2}(M\lambda_m - \Delta\lambda_m)$$

In the above equations, f_m is the frequency of modulation and M is an integer that is equal to the number of full modulation wavelengths in the distance $2d$. As illustrated in Figure, there are four full modulation wavelengths (M = 4) in the roundtrip distance from the transmitter to the target and back to the transmitter.

Ultrasonic TOF Systems

This is the most common technique employed on indoor mobile robots to date, which is primarily due to the ready availability of low cost systems and their ease of interface.





Ultrasound waves are transmitted in a medium. When the pulse reaches an another medium, it is totally or partially reflected, and the elapsed time from emission to detection of the reflected pulse is measured. This time depends on the distance and the velocity of the sound. When sound travels with a known velocity V_s T_f time elapsed between the outgoing signal and its incoming echo is a measure of the distance d to the object causing the echo.

$$d = \frac{VT_f}{2}$$

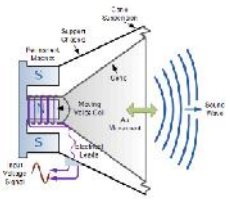
A typical value for the speed of sound in air at 1 atm pressure and room temperature is 343 m/s but the speed of sound is influenced by air pressure, air temperature, and the chemical composition of air. Measuring distances in an environment with large temperature gradients can result in erroneously calculated distance.

The transmitter and the receiver could be the same device, but they are separated for clarity. The oscillator generates an electric signal with a typical frequency of 40 kHz. This electric signal is transformed into mechanical vibrations of the same frequency in the transmitter. These vibrations generate sound waves that are reflected by the object. The reflected sound echo causes an electric signal in the receiver. Sound is a vibration in matter. It propagates as a longitudinal wave, i.e., the displacement in the material is in the direction of the sound wave propagation.

Most ultrasound transducers convert electric energy to mechanical energy and vice versa. The most common types of in-air transducers are: .Mechanical, Electromagnetic, Piezoelectric, Electrostatic, Magnetostrictive.

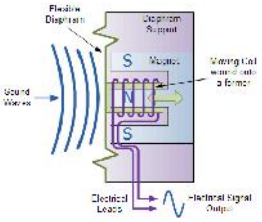
Electromagnetic transducers such as loudspeakers and microphones can be used for ultrasonic wave generation used up to approximately 50 kHz, but they are mainly suited for lower frequencies. Loudspeakers and microphones are normally audio sound transducers that are classed as "sound actuators" but their micromechanical analogies can reach higher sound frequencies.

Moving coil transducers: The loudspeakers and microphones can be built up as basic moving coil transducer by applying virtues of electromagnetic effects.



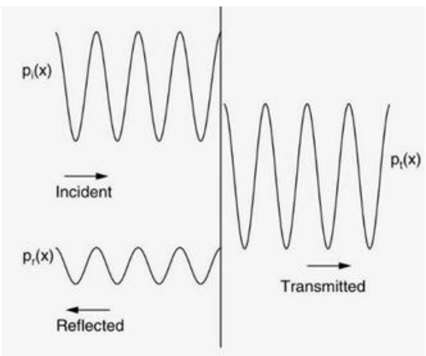
When an analogue signal passes through the voice coil of the speaker, an electro-magnetic field is produced and whose strength is determined by the current flowing through the "voice" coil, which in turn is determined by the volume control setting of the driving amplifier or moving coil driver. The electro-magnetic force produced by this field opposes the main permanent magnetic field around it and tries to push the coil in one direction or the other depending upon the interaction between the north and south poles.

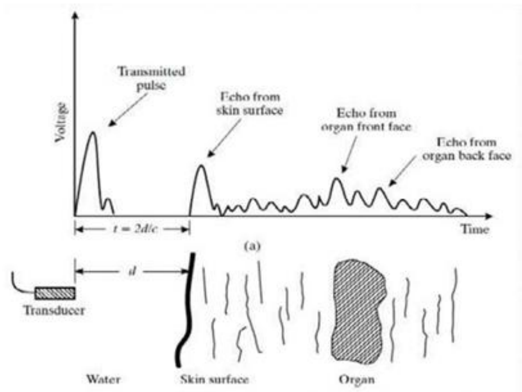
As the voice coil is permanently attached to the cone/diaphragm this also moves in tandem and its movement causes a disturbance in the air around it thus producing a sound.



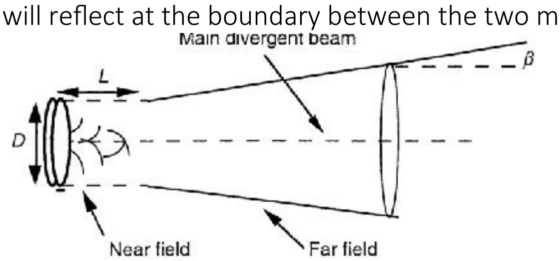
The construction of a dynamic microphone resembles that of a loudspeaker, but in reverse. It has a very small coil of thin wire suspended within the magnetic field of a permanent magnet. As the sound wave hits the flexible diaphragm, the diaphragm moves back and forth in response to the sound pressure acting upon it causing the attached coil of wire to move within the magnetic field of the magnet. The movement of the coil within the magnetic field causes a voltage to be induced in the coil as defined by Faraday's law of Electromagnetic Induction.

The resultant output voltage signal from the coil is proportional to the pressure of the sound wave acting upon the diaphragm so the louder or stronger the sound wave the larger the output signal will be, making this type of microphone design pressure sensitive.



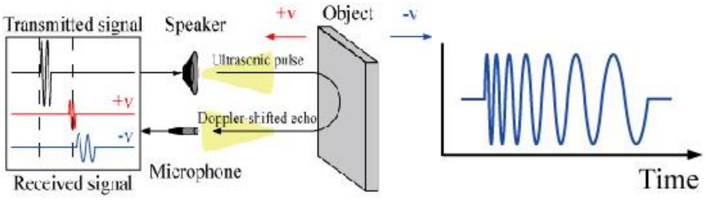


An acoustic wave has an intensity and a usually unwanted phenomenon arises when the sound wave has to pass from one medium to another medium with different characteristic impedance characteristic impedance, a part of the wave intensity will reflect at the boundary between the two media.



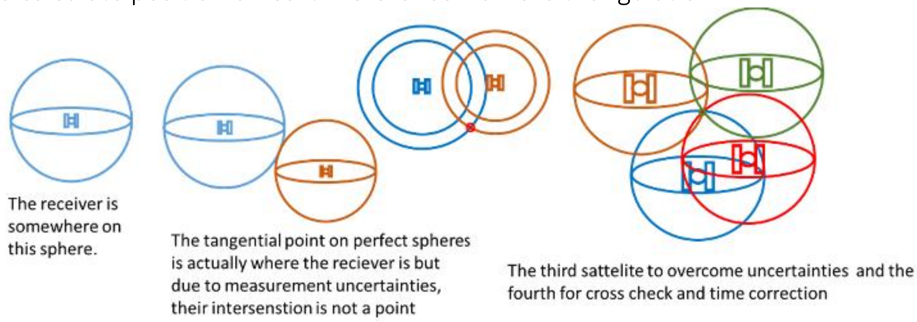
The electric energy is converted into mechanical vibrations of a membrane in the transmitter. Second, the vibrations (the sound wave) have to pass through the boundary between the membrane (usually a solid material) and free air. Because

the transmitter membrane and the free air have different characteristic impedances, some of the acoustic intensity is reflected. Therefore ultrasonic tof displacement sensors have a minimum measurement limit as can be seen in figure.
The method of velocity measurement using ultrasonic waves is based on the pulse-Doppler method. When the object is moving, due to the Doppler effect introduced by the motion of the object, the reflected echo is Doppler-shifted. The frequency of Doppler-shifted echo is increased or decreased in proportion to the velocity of the object. Therefore, the pulse-Doppler method determines the velocity of the object by measurement of increase or decrease in the frequency



GPS

An example of a TOF one-way (active receiver) system that uses radio frequencies is the global positioning system (GPS).
GPS is a space based satellite navigation system that provides location and time information anywhere, anytime and in all weather conditions. GPS uses these "man-made stars" as reference points to calculate positions accurate to a matter of meters.
The Global Positioning System allows a GPS receiver to determine its position by using a simple formula: Velocity x Time = Distance. GPS satellites continuously transmit digital radio pulses at precise, known times. So by measuring the exact instant when the pulses arrive, the receiving GPS equipment can determine the distance to each satellite.
The clocks on board the satellites are all extremely accurate, while the clock in the GPS receiver is not. So a GPS receiver calculates what are called pseudo-ranges ("false" ranges), which are approximate calculated distances (as a measurement of time) to every satellite the receiver has acquired.
Eventually, in order for the GPS receiver to determine a precise position it will have to get its own clock synchronized with the satellite clocks. For this purpose, GPS sattelites send a time codded pulse array to receiver. The receiver arranges its clock if there is a difference between durations on received codded signal and the information provided from satellite about that signal. By this means, a receiver can calculate its distance to the specific satellite.
The technique used to calculate position on earth reference frame is triangulation.



How a Receiver Determines Its Position: The GPS receiver calculates a rough location somewhere on three dimensional sphere, which has actually a diameter of calculated distance value.
In a perfect world, where both satellite and receiver clocks were perfectly synchronized with each other, an accurate position could be determined from just two satellites. However, all the signals from satellites are random numbers with some distribution which makes intersection point of spheres a 3D volume.
For a GPS receiver to achieve *three-dimensional* (3D) positioning it needs to acquire four or more satellite signals. A 3D position is comprised of X and Y (horizontal), Z (vertical) positions, and precise time The receiver's processor uses the first three to solve below equation and the fourth satellite pseudo-range as a timing cross check to estimate the discrepancy in its own ranging measurements and calculate the amount of time offset needed

$$\begin{Bmatrix} (x_0-X_1)^2+(y_0-Y_1)^2+(z_0-Z_1)^2=d(\Delta t_1,\varepsilon)^2 \\ (x_0-X_2)^2+(y_0-Y_2)^2+(z_0-Z_2)^2=d(\Delta t_2,\varepsilon)^2 \\ (x_0-X_3)^2+(y_0-Y_3)^2+(z_0-Z_3)^2=d(\Delta t_3,\varepsilon)^2 \\ (x_0-X_4)^2+(y_0-Y_4)^2+(z_0-Z_4)^2=d(\Delta t_4,\varepsilon)^2 \end{Bmatrix}$$