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Incluir los agradecimientos, si procede.

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Resumen

Escriba aquí un resumen de la memoria en castellano que contenga entre 100 y 300 palabras. Las palabras clave serán entre 3 y 6.

Palabras clave: palabra clave 1; palabra clave 2; palabra clave 3; palabra clave 4

Abstract

Insert here the abstract of the report with an extension between 100 and 300 words.

Keywords: keyword1; keyword2; keyword3; keyword4

Introduction

1.1. THE HOT BIG BANG MODEL

The most accepted model for the origin of the universe is the Big Bang model, that models the beginning of the universe as a hot dense state. The Big Bang surprisingly to some conveys no "bang", but the sudden existence of all the matter in the universe, in the shortest of times, in the smallest of spaces, about 13.8 billion years ago. After an unthinkable small interval of time, the universe began a short period of rapid expansion known as *cosmic inflation*, in which the universe grew by a factor 10^{27} in a mere 10^{-33} seconds. This inflation is thought to be due to the inflaton, a quantum scalar field. It is theorized that it is the inflaton's vacuum energy what caused the universe to expand as greatly.

As any quantum field¹ the inflaton presents fluctuations. This means, even in the vacuum state² there is constant creation and annihilation of particles. These fluctuations are what cause anisotropies in the matter distribution of the universe, fact that will be important later in this work.

After the inflation phase, the universe cooled enough for what is known as the Quark-Gluon plasma to form. In this state, temperatures were high enough as to consider relativistic the random motion of the particles in it. After some cooling due to cosmic expansion, the combination between quarks to form hadrons was allowed, leading to what is known as the hadronic epoch. However, due to the short mean free path of the photons, the universe is still opaque to electromagnetic radiation.

As the universe kept expanding the densities decreased and the temperatures cooled, the existence of atoms was starting to be allowed, the *He* and *H* atoms. This period would finish at the universe age of 380,000 years, moment known as recombination. Recombination is thought of as the time at which the Thomson Scattering mechanisms stop

¹Quantum fields are a tool used by Quantum Field Theory (QFT) to more accurately describe particles and their interactions, at high enough energies.

²To define vacuum in QFT is not as easy a task as it was in classical mechanics (or even non-relativistic quantum mechanics). These details go beyond the scope of this paper, and thus will not be dealt with.

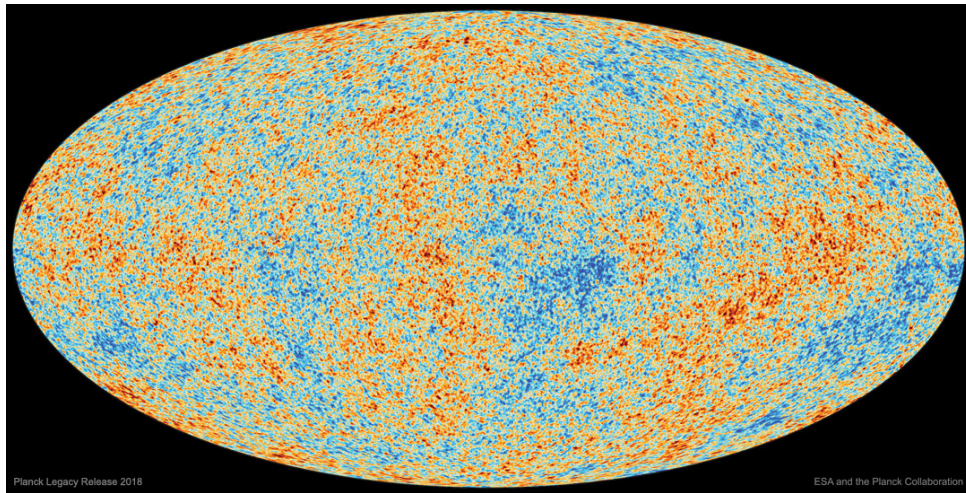


Figura 1.1: The all-sky map of CMB anisotropies as seen by Space-based Observatory Planck (cita collaboration 2018). The colors in this map represent the fluctuations of the mean $T = 2.7\text{ K}$ with fluctuations of 10^{-5} with respect to the average temperature. Red means higher temperature than the average, whilst blue means lower temperature than the average.

being effective (the scattering cross section of this process becomes negligible and thus the photon mean free path grows considerably). As soon as recombination ends, the thermally activated photons which are no longer energetic enough to interact with the electrons now travel freely through space. This emission is known as the Cosmic Microwave Background (CMB) and is the oldest direct observation using electromagnetic radiation we can take of the universe.

Though the name ‘recombination’ implies the fact that the universe used to be ‘combined’ and then ceased to be so, it just comes from the fact that recombination was theorized before the Big Bang theory was thought of.

1.2. COSMIC MICROWAVE BACKGROUND

We see in the figure 1.1 the CMB as observed by the Planck collaboration (cita collaboration2018). The radiation we observe is the photons that were emitted about 13.8 billion years ago. Since the CMB appears as a result of the thermal photons emitted by the electrons in the primordial plasma, it offers great insight into what the plasma looked like, and the way it behaved.

The Cosmic Microwave Background was discovered in 1965 as a serendipity by Penzias and Wilson (cita penzias and wilson). They observed a noise signal, uniformly distributed³

³It was not actually uniformly distributed, since there was a small doppler shift due to the Earth’s relative movement to the CMB. Surprisingly, even after removing this and other similar effects, it still presents minute fluctuations. These fluctuations, as it will be seen in the next sections contain a great deal of information on the composition of the universe and explains the origin of structure formation.

from every direction, day or night, summer or winter, almost as if it came directly from the origin of the universe. This discovery was considered to be solid evidence for the Big Bang model and more importantly, the beginning of the modern cosmology. All of this became the reason Penzias and Wilson received a Nobel prize 13 years later, in 1978.

Since what is being measured are the photons left from recombination, which corresponds to a thermal radiation curve, we may use Wien's displacement law

$$T = \frac{b}{\lambda} \quad (1.1)$$

with $b \approx 2.897 \text{ mmK}$ Wien's constant, T the black body radiation and λ the wavelength at which the spectral radiation intensity is maximum to calculate the corresponding temperature to the measured wavelength. Using Planck's law, the measured temperature is 2.7 K which corresponds to a measured wavelength of 1.06 mm (microwave radiation, as the name Cosmic *Microwave* implies).

In 1991 anisotropies in the CMB were first discovered, by the COBE satellite (citar SmootMather) later earning Smoot and Mather a nobel prize. As of 2023 the most precise measurements correspond to the Planck experiment in 2018 (citar Planck2018) by the European Space Agency. These anisotropies can be seen in 1.1.

Of course, 2.7 K was not the temperature of the plasma at recombination, as it was approximately hotter by a factor $z = 1090$, or $\approx 3000 \text{ K}$. The reason we measure such smaller temperatures is because of the expansion of the universe. If today ($t = t_0$) some radiation of wavelength λ_o is observed, that somehow is known to have been travelling for some time Δt will have stretched due to the expansion of the universe. In other words, the wavelength λ_e of the emitted radiation was smaller by a factor⁴ $a(t')^{-1}$, with $t' = t_0 - \Delta t$ being the earlier time at which the radiation was emitted, and $a(t_0) = 1$ by definition. By Wien's displacement law (1.1), this corresponds to a higher temperature by a factor $a(t')$.

Thus, the CMB becomes crucial in explaining the large scale structure of the universe, since the photons that decoupled from the plasma at recombination wasted more energy leaving denser regions behind losing thermal energy in the process. Appearing at a slightly lower temperature (gravitational redshift). On the contrary, those in void regions will appear hotter, being blueshifted. Therefore, temperature fluctuations in the CMB correspond to density fluctuations in the early universe.

1.3. BARYON ACOUSTIC OSCILLATIONS

Before recombination, both matter and photons were coupled into the same fluid which we have called the primordial plasma. The particles in the plasma interacted primarily with one another through gravity and electromagnetism, depending on the type of matter considered.

As already mentioned, matter was not distributed homogenously. At some point in time before recombination one could find 'lumps' of dark and baryonic (standard) matter. Combining the restoring force of the gravitational attraction between dark and baryonic matter with itself and with one another, and the repulsion caused by the radiation pressure due to the Thomson Effect between baryons and photons, the results are pure acoustic

⁴The factor $a(t)$ is known as the scale factor of the universe, and will be explained with further detail later in the work.

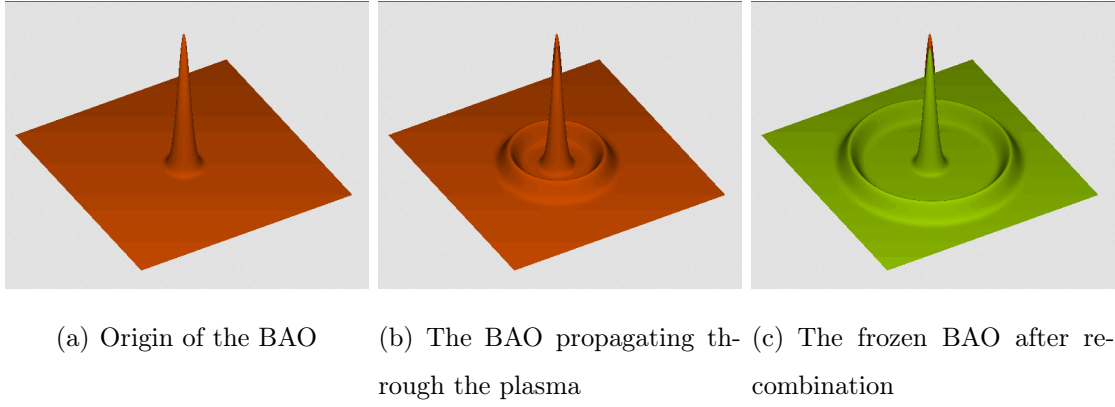


Figura 1.2: Different stages of the Baryon Acoustic Oscillations. Courtesy of the image (citar <https://lweb.cfa.harvard.edu/deisenst/acousticpeak/anim.gif>)

waves propagating through the plasma, with the dark matter lumps being in the center of these waves. Since the baryonic matter is dragged by these sound waves, they are called Baryon Acoustic Oscillations (BAO).

The waves would propagate throughout the plasma as long as the baryon-photon interaction was strong enough i.e. up to recombination, at which point they froze in time leaving higher density regions. Higher density means higher gravitational intensity, which in turn means higher galaxy proliferation in spherical distributions. These spherical distributions (which can be measured in the CMB) are what is known as the large scale structure of the universe.

At big enough distances, the radii (r_s) of these spheres, also called the sound horizon is used as a ‘cosmic ruler’. Big scale measurements are calculated in terms of r_s , which is measured from the CMB. This means it needs to be calibrated from external information. r_s has been measured from the CMB to be around 150 Mpc or 500 million lightyears. To give an idea of the size of r_s , the radius of the observable universe is around 100 times r_s .

Given the large dimensions of this cosmic ruler and the homogeneity of the universe on large scales, this ruler is only affected by cosmological expansion rather than late-time gravitational effects. Therefore, it has a constant comoving⁵ size throughout the universe.

These structures were observed for the first time in 2005 simultaneously both by the 2dF Galaxy Redshift Survey (cita 2dF Cole 2005) and the Sloan Digital Sky Survey (cita Eisenstein 2005), the results of which can be seen in the figure 1.3. In these pictures one sees the correlation function $\xi(r)$ and the power spectrum $P(k)$ (though in the figure 1.3(b) it is called W_k). These are the main tools for the study of the BAO. The correlation function $\xi(s)$, with s being a distance variable measures the frequency of the separation between any two galaxies. If the BAO hypothesis is true, then one would find a local maximum at r_s , the radius of the frozen spherical waves.

The other tool for studying the BAO is the power spectrum seen in 1.3(b). It is, without need of more detail, the Fourier transform of the $\xi(s)$ function. Indeed, since there is a repeating pattern of wavelength r_s , one would find local maxima in the spectrum at integer multiples of $k = 2\pi/r_s$.

⁵‘Comoving’ meaning the distance one would measure had the expansion of the universe not existed



(a) The correlation function $\xi(s)$ as measured by the Sloan Digital Sky Survey (SDSS) and 2dF collaboration (Eisenstein et al. 2005). (b) The power spectrum as observed by the 2dF collaboration (Cole et al. 2005).

Figure 1.3: First detections of BAO

1.4. CURVATURE, DARK MATTER AND THE EXPANSION OF THE UNIVERSE

After Hubble discovered the expansion of the universe through Hubble's Law (Hubble 1929), a great deal of studies concerning the expansion of the universe started. The most relevant result of those for this report are Friedmann's equations.

$$v = H_0 d \quad (1.2)$$

With v the recession speed (the speed at which some point in space is receding only considering the expansion of the universe), $H_0 = 100h \text{ km s}^{-1} \text{ Mpc}^{-1}$ Hubble's constant, h a factor that parametrizes our ignorance on the true value of H_0 (estimated to be around 0.67), and d the distance of said point, a great deal of studies concerning the expansion of the universe started. The most relevant result of those for this report are Friedmann's equations.

$$H^2(t) := \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G\rho}{3} + \frac{\Lambda c^2}{3} - k\frac{c^2}{a^2} \quad (1.3)$$

$$3\frac{\ddot{a}}{a} = \Lambda c^2 - 4\pi G\left(\rho + \frac{3p}{c^2}\right) \quad (1.4)$$

In these equations we see many new parameters. $H(t)$ is a generalization of H_0 , H_0 being the value of $H(t)$ at $t = t_0$ where t_0 is the age of the universe. $a(t)$ is the scale factor of the universe, meaning that if a certain length measurement Δx was taken at time t_1 , then that same measurement would be $\frac{a(t_2)}{a(t_1)}\Delta x$ at t_2 . G is the Newton's gravitational constant, ρ the density of the universe (including baryonic, dark matter, radiation and neutrinos), Λ is the cosmological constant which contains information about Dark Energy. Finally we see k , which is the spatial (Gaussian) curvature of the universe. This is, asymptotical curvature.

These equations are a result of the Friedmann–Lemaître–Robertson–Walker metric

$$ds^2 = -c^2 dt^2 + a^2(t) \left(\frac{dr^2}{1 - kr^2} + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2 \right) \quad (1.5)$$

which are a direct result of solutions to Einstein's field equations of General Relativity, which will not be covered in this report. In (1.5) one sees the usual components in a flat space Minkowskian metric

$$ds^2 = -c^2 dt^2 + dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\phi^2 \quad (1.6)$$

and some new terms, $a(t)$ and k . $a(t)$ is the aforementioned scale factor, and k a measure of the curvature of the universe. It is easier now to see that $a(t)$ is crucial in the way lengths are measured, being an overall factor in the spatial part that is homogeneous but time-dependent. Also, one can notice how having different types of universe affects differently to the metric. For example $k = 0$ yields (as one would expect) a flat universe. $k > 0$ corresponds to a universe with spherical geometry and $k < 0$ to a universe of hyperbolic geometry.

If one managed to solve (1.3), the result would be $a(t)$, a description of the history of the expansion of the universe. Moreover, it is also important to notice the relationship between the expansion of the universe and the distribution of matter in the universe.

From (1.3) we define the density parameter Ω_m as $\frac{\rho}{\rho_c}$, with the critical density $\rho_c = \frac{3H_0^2}{8\pi G}$, which represents the transition point (for a universe without cosmological constant) between an ever expanding universe with negative curvature (open universe) and a collapsing universe with positive curvature (closed universe). Similarly from the rest of the terms in the equation (1.3)

$$\Omega_\Lambda = \frac{\Lambda c^2}{3H^2}, \Omega_k = -\frac{kc^2}{H^2 a^2} \quad (1.7)$$

Ω_Λ corresponds to the density of dark energy in the universe, while Ω_k is not a density *per se*, but is related to the total energy content of the universe, determining its curvature. These parameters are what define the certain cosmology we are using, and obey the cosmic sum rule

$$1 = \Omega_m + \Omega_\Lambda + \Omega_k \quad (1.8)$$

Which is just a result of dividing (1.3) evaluated at present time, by H_0^2 .

Historically, the concept of cosmological expansion appeared when Hubble observed that the radiation of the nearby galaxies was all shifted towards the red end of the spectrum. Of course, since the universe is expanding and the distance between two points increases with time, the wave length of a certain radiation would also be affected by this expansion. This stretching of the wave length is what is known as *redshift*

$$z = \frac{\lambda_o - \lambda_e}{\lambda_e} = \frac{\lambda_o}{\lambda_e} - 1 \quad (1.9)$$

Being λ_o the observed wavelength and λ_e the emitted wavelength of the considered radiation. z is a measure of how much the universe stretched while the radiation travelled, and it can be related to $a(t)$ through

$$\frac{\lambda_o}{\lambda_e} = 1 + z = \frac{a(t_o)}{a(t_e)} \quad (1.10)$$

Which means that z is a temporal variable measuring the time the radiation travelled through the universe.

However, this redshift z should not be confused with the redshift caused by the Doppler Effect of objects moving away. The processes are different in origin, since cosmological redshift does not need relative movement to shift the radiation towards red wavelengths, it is the expansion of the universe what stretches the wavelength. On the contrary, the Doppler Effect appears when pulses emitted at regular time are emitted further away due to the movement of the wave source.

We thus define the comoving distance $\Delta x'$ of a measurement Δx as

$$\Delta x' = \frac{\Delta x}{a(t)} = (1+z)\Delta x \quad (1.11)$$

i.e. the distance one would have measured had the expansion of the universe not existed.

With these definitions we can define the observables we are interested in calculating/-measuring. Firstly, through (1.3) we calculate $H(z)$ as

$$H(z) = H_0 \sqrt{\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda} \quad (1.12)$$

We also define the function of z $D_H(z)$ known as the Hubble distance

$$D_H(z) = \frac{c}{H(z)} \quad (1.13)$$

Note that for $z = 0$ D_H gives us an idea of the distance at which the recession speed is greater than the speed of light in the vacuum, which is a direct consequence of (1.2). D_H can also be used to estimate the order of magnitude of the observable universe.

Through the Hubble distance we define the comoving distance

$$D_C(z) = \frac{c}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_m(1+z')^3 + \Omega_k(1+z')^2 + \Omega_\Lambda}} \quad (1.14)$$

From this expression one defines the angular diameter distance for some redshift z

$$D_A(z) = \begin{cases} \frac{D_H}{(1+z)\sqrt{\Omega_k}} \sinh \left[\sqrt{\Omega_k} D_C / D_H \right] & \Omega_k > 0 \\ \frac{1}{1+z} D_C & \Omega_k = 0 \\ \frac{D_H}{(1+z)\sqrt{|\Omega_k|}} \sin \left[\sqrt{|\Omega_k|} D_C / D_H \right] & \Omega_k < 0 \end{cases} \quad (1.15)$$

And the comoving trasverse angular diameter distance as

$$(1.16)$$

1.5. A COLD DARK MATTER MODEL

In the definitions in (1.7) the parameters Ω were introduced. This definitions, plus the definition of the density parameter Ω_m are part of the set of parameters that form the Λ Cold Dark Matter (Λ CDM) model.

This model is the simplest available way of explaining the current state of the universe, with 6 different constants. The name is derived from two of the biggest components of the universe, Λ (the cosmological constant, related to Dark Energy) and Cold Dark Matter, which is thought to be

- **Cold:** Non relativistic ($v \ll c$)
- **Non baryonic:** Made up of non baryonic matter i.e. anything other than protons and neutrons (and by convention, electrons).
- **Disipationless:** Since Dark Matter does not interact with the electromagnetic field, it can not dissipate temperature through photon emission.
- **Collisionless:** Dark matter particles can only interact through gravity and possibly, the weak force and so they do not collide with one another.

The information on this cold dark matter is inside Ω_m , since the density ρ in

$$\Omega_m = \frac{\rho}{\rho_c} = \frac{\rho_b + \rho_{\text{CDM}}}{\rho_c} \quad (1.17)$$

Allowing us to define two new density parameters $\Omega_b = \frac{\rho_b}{\rho_c}$ and $\Omega_c = \frac{\rho_{\text{CDM}}}{\rho_c}$, which are part of the six free parameters that define a certain cosmology. These are Ω_b , Ω_c , H_0 , the optical density of reionization τ_{reio} , the amplitude of the primordial power spectrum A_s , the spectral index of the primordial power spectrum n_s . Note there is no special choice of parameters, these are just the free parameters chosen for this work.

In this work, an extension of the Λ CDM model is considered. Though the standard cosmological model considers a flat universe, the curvature parameter will not be fixed to 0 and is therefore allowed to be a free parameter, adding a new degree of freedom to the standard model (not to be confused with the particle physics standard model). This model can be further extended by considering the mass of the neutrinos, the quintaessential force (dark energy)...

The fiducial (starting) values of these parameters that will be used in this work are

- $\Omega_b = 0.0481$
- $\Omega_c = 0.2604$
- $H_0 = 67.6 \text{ km s}^{-1} \text{ Mpc}^{-1}$
- $\tau_{\text{reio}} = 0.09$
- $A_s = 2.04031526769 \cdot 10^{-9}$
- $n_s = 0.97$

And Ω_k that will vary between -0.2 and 0.2 .

From these free parameters, one derives some parameters. Of those, the main interest is in Ω_Λ , r_s , D_H , and D_A ,

- $r_s = 147.784 \text{ Mpc}$
- $D_H/r_s = 18.7$
- $D_A/r_s = 18.3$

And Ω_Λ will vary between 0.49 and 0.89 .

Finally, we define two more parameters α_{\parallel} and α_{\perp} . These parameters measure the distortion of the measurements in two different directions. α_{\parallel} is related to the distortion parallel to the line of sight, and α_{\perp} , perpendicular to the line of sight. They are defined by

$$\alpha_{\parallel} = \frac{[D_H(z)/r_s]}{[D_H(z)/r_s]^{\text{fid}}}, \alpha_{\perp} = \frac{[D_A(z)/r_s]}{[D_A(z)/r_s]^{\text{fid}}} \quad (1.18)$$

z being the redshift at which the measurements were taken.

Objectives

The general objective of this final degree work is to study the behavior of baryon acoustic oscillation (BAO) observables, namely the sound horizon distance r_s , the Hubble parameter distance D_H , and the angular diameter distance D_A , as a function of the curvature parameter Ω_k . To achieve this objective, the following specific objectives are proposed:

1. Review the theoretical background of BAO observables, including their physical origin and mathematical formulation, and become familiar with the software tools Rustico, BRASS, and Python for data analysis and visualization.
2. Learn to use these software tools for data preprocessing, analysis, and visualization of BAO-related cosmological data sets, particularly those related to the curvature parameter Ω_k .
3. Investigate the impact of different values of Ω_k on the behavior of BAO observables, and determine how this affects our understanding of the expansion history of the universe.
4. Analyze the most recent observational data on BAO observables, obtained from experiments such as SDSS, BOSS, and eBOSS, and compare the results with theoretical predictions for different values of Ω_k .
5. Evaluate the strengths and limitations of using BAO observables to constrain the value of Ω_k and its impact on other cosmological parameters.
6. Specific data analysis software development.
7. Learn to control computer clusters via ssh.

Together, these objectives will provide a comprehensive understanding of the behavior of BAO observables for different values of Ω_k , and their role in constraining the curvature parameter and other cosmological parameters.

Methods and materials.

For this work, many different tools were used, which will be categorized in hardware, software and mathematical tools.

In terms of hardware, the author was granted access to the *FQM-378* clusters in the Universidad de Córdoba. Access to these clusters was crucial for the calculations done throughout the work, reducing the time needed for each calculation in several orders of magnitude. Besides the clusters, the author also needed his own personal computer, mainly to remotely access the clusters and also for other types of calculations that could not have been done from the clusters. These calculations include among other things, plotting of figures.

In terms of software, the main tools for this work were J. Lesgourges, T. Tram and N. Schoenberg's work, Cosmic Linear Anisotropy Solving System (CLASS), Hector Gil-Marín's works Rapid foUrier STatIstics COde (RUSTICO) and Bao and Rsd Algorithm for Spectroscopic Surveys (BRASS).

Conclusiones

En este trabajo ...

Conclusions

In this work ...

Bibliografía

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Anexo: Ejemplo para introducir código Matlab

```
1 %% 3-D Plots
2 % Three-dimensional plots typically display a surface
3 % defined by a function in two variables,  $z = f(x,y)$  .
4 %%
5 % To evaluate  $z$ , first create a set of  $(x,y)$  points
6 % over the domain of the function using meshgrid.
7     [X,Y] = meshgrid(-2:.2:2);
8     Z = X .* exp(-X.^2 - Y.^2);
9 %%
10 % Then, create a surface plot.
11     surf(X,Y,Z)
12 %%
13 % Both the surf function and its companion mesh display
14 % surfaces in three dimensions. surf displays both the
15 % connecting lines and the faces of the surface in color.
16 % Mesh produces wireframe surfaces that color only the
17 %lines connecting the defining points.
```

Anexo: Ejemplo para introducir código ISE

```
1 library IEEE;
2     use IEEE.STD_LOGIC_1164.ALL;
3     use IEEE.STD_LOGIC_ARITH.ALL;
4     use IEEE.STD_LOGIC_UNSIGNED.ALL;
5 -- Uncomment the following library declaration if
6 -- instantiating any Xilinx primitive in this code.
7 -- library UNISIM;
8 -- use UNISIM.VComponents.all;
9
10 entity counter is
11     Port ( CLOCK : in  STD_LOGIC;
12           DIRECTION : in  STD_LOGIC;
13           COUNT_OUT : out STD_LOGIC_VECTOR (3 downto 0));
14 end counter;
15
16 architecture Behavioral of counter is
17 signal count_int : std_logic_vector(3 downto 0) := "0000";
18 begin
19 process (CLOCK)
20 begin
21     if CLOCK='1' and CLOCK'event then
22         if DIRECTION='1' then
23             count_int <= count_int + 1;
24         else
25             count_int <= count_int - 1;
26         end if;
27     end if;
28 end process;
29 COUNT_OUT <= count_int;
30 end Behavioral;
```