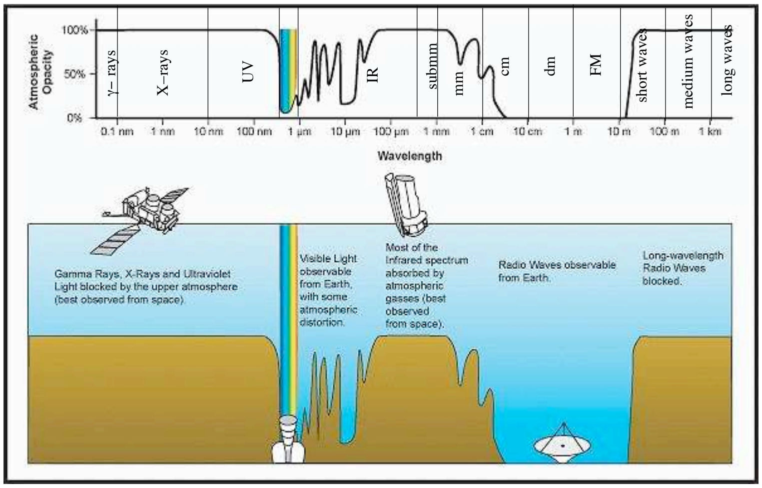
Chapitre 1

Introduction

In our everyday human experience, we see that light has measurable properties. It has intensity (brightness), and it has color. The intensity gives an indication of the number of light ”waves” or ”particles” (called photons) coming from an object. The color is a measure of the energy contained in each photon. The colors of the rainbow (red, orange, yellow, green, blue, violet) denote the energies of light waves that our human eyes can see and interpret. This ”color” or ”energy” range is called the visible spectrum. Red photons of light have the least energy, violet photons carry the most energy. Until fairly recently, all of our astronomical knowledge came from the detailed study of visible light from astronomical objects.

But the visible spectrum is only a tiny portion of the total electromagnetic (EM) spectrum, as can be seen in the following figure. Radio, TV, and microwave signals are all light waves, they simply lie at wavelengths (energies) that our eyes do not respond to. On the other end of the scale, high energy UV, x-ray, and γ-ray photons carry a lot of energy compared to the visible and radio waves.



When we look at the Universe in a different ”light”, i.e. at ”non-visible” wavelengths, we probe different kinds of physical conditions and we can see new kinds of objects. For example, high-energy gamma-ray and X-ray telescopes tend to see the most energetic dynamos in the cosmos, such as active galaxies, the remnants from massive dying stars, accretion of matter around black holes, and so forth. Visible light telescopes best probe light produced by stars. Longer-wavelength telescopes best probe dark, cool, obscured structures in the Universe : dusty star-forming regions, dark cold molecular clouds, the primordial radiation emitted by the formation of the Universe shortly after the Big Bang. Only through studying astronomical objects at many different wavelengths are astronomers able to piece together a coherent, comprehensive picture of how the Universe works.

Most of the EM spectrum gets absorbed or blocked by the atmosphere, and it is a good thing for our everyday human well being. Just a tiny portion of ultraviolet light leaking through the atmosphere is enough to give us a painful sunburn if we aren't careful. What Earth would be like if ultraviolet or X-ray light could get through the atmosphere ? Just like Mars. The atmosphere is "good news" from the perspective of life on Earth. But the atmosphere is "bad news" if we want to see the Universe at these wavelengths.

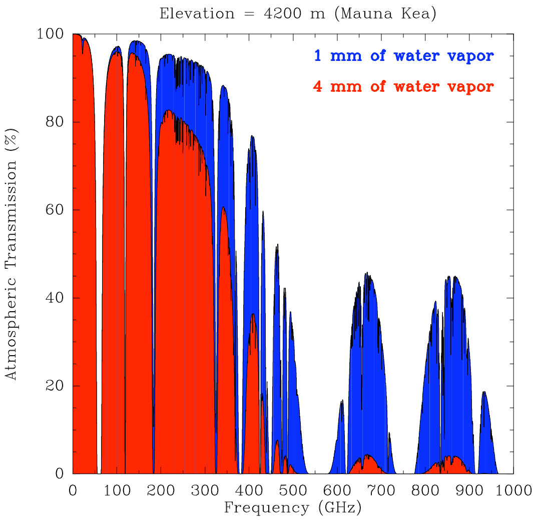
At the opposite extreme, most radio- and visible- wavelength observations are unimpeded by the atmosphere ; the incoming photons can travel right through. The atmosphere is transparent at such wavelengths.

Submillimeter-wavelength (0.3 - 1.0 mm) astronomy is perhaps the last wholly unexplored wavelength frontier. Why ? Submillimeter ("microwave") astronomy is technically very difficult due to the sheer complexity of the instrumentation and to the "opaqueness" of the atmosphere in microwave light.

At submillimeter wavelengths, ambient atmospheric water vapor will absorb (block) incoming light. At low elevations, where most water vapor resides, the atmosphere is very opaque at submillimeter wavelengths ; the abundant water vapor absorbs any incoming submillimeter photons before they can reach the telescope. At higher elevations, however, the water content decreases substantially. By minimizing the atmospheric water vapor, one improves the transparency of the atmosphere and makes astronomical observations possible. It is for this reason that infrared and submillimeter observatories are built as high as possible ; by being above some of the atmosphere, the radiation from astronomical sources is much less attenuated.

To demonstrate how important a dry site is to a submillimeter observatory, look at the following plot :

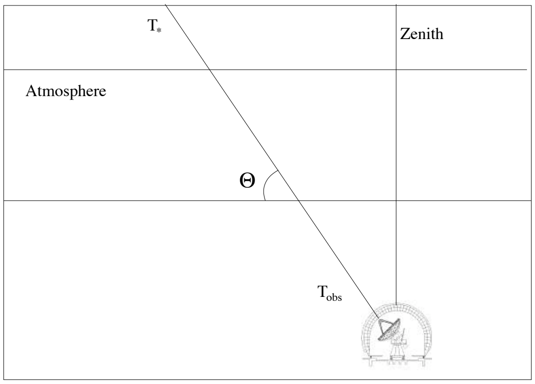
The atmospheric transmission at microwave frequencies is plotted (with ATPLOT) at an



elevation of 4200 m (Mauna Kea observatory) for two amounts of atmospheric water : 1 mm and 4 mm of precipitable water vapor (PWV). 4 mm of PWV means that if every molecule of water vapor above you could be condensed into an ocean, it would be 4 mm deep. At a very high, dry site under excellent conditions, you might expect to see 1 mm of PVW. Lower frequency observations (below 200 GHz, a.k.a "millimeter"-wave astronomy) can be performed under conditions when submillimeter observations are impractical or impossible. we can define the athmospheric opacity by the optical depth, τ :

$$\tau = \int_L k dL \tag{1.1}$$

where k is the absorption coefficient and L the length the wave propagates in the atmosphere. There is a direct dependence between the distance L and the elevation angle of the external source as illustrated on the following figure, with a plane atmosphere approximation.



The external radiation intensity I_1 is attenuated by an exponential factor when observed through the atmosphere, τ is the optical depth, in nepers, and Θ the elevation angle :

$$T_{obs} = T_* e^{\frac{-\tau}{sin\Theta}} \tag{1.2}$$

1mm of PWV corresponds to an opacity of 0.05 observed at the zenith.

Millimeter and submillimeter-wave observations provide important informations for the studies of atmospheric chemistry and of astrochemistry (molecular clouds, stars formation, galactic study, comets and cosmology). But, these observations depend strongly on instrumentation techniques and on the site quality. New techniques or higher detector performances result in unprecedented observations and sometimes, the observational needs drive developments of new detector technologies, for example, superconducting junctions (SIS mixers) because its high sensitivity in heterodyne detection in the millimeter and submillimeter wave range (100 GHz - 700 GHz), HEB (Hot Electron Bolometer) mixers which are being developed by several groups for application in THz observations.

Chapitre 2

Heterodyne technique

The heterodyne conversion uses a local oscillator to mix a radio frequency signal to a more convenient intermediate frequency (IF). The mixer generates upper and lower sidebands, either of which may be filtered out if desired.
A local oscillator is a device used to generate a signal which is beat against the signal of interest to mix it to a different frequency. Power is supplied by solid-state Gunn oscillator which are phase locked. The output is used to drive a Schottky diode frequency multiplier. Several local oscillators can be strung in series to form a so-called ”LO chain.”

A mixer is a device used to multiply signals which has a nonlinear response to an electric field. In principle, any device with a nonlinear relation between input voltage and output current can be used for this, but the derivation of its properties are most simple for a pure quadratic characteristic : I=αU^2.
Possible devices include bolometers, photoconductors, classical (Schottky) diodes, and quantum non-linear devices (Superconductor-Insulator-Superconductor receivers or Josephson junction mixers). Bolometers and photodetectors have limited response time and therefore limited IF bandwidths. Classical diodes cannot have gain and typically have I-V characteristics whose nonlinearity involves a semiconductor gap of $\sim$ 1 V. Quantum nonlinear devices can have gain, and have a superconducting gap of a few mV, as well as having low power requirements (Phillips 1988). Two diodes for which I $\propto$ V^2 can be used as multipliers by inputing sums and differences of two voltages and differencing :

$$I = (V_1 + V_2)^2 - (V_1 - V_2)^2 = 4V_1V_2 \tag{2.1}$$

Mixers combine a radio frequency [RF] signal and a local oscillator [LO]. The result of the multiplication for two cosinusoidal signals is :

$$S = cos(w_{LO}t)cos(w_{RF}t) = \frac{1}{2}cos[(w_{LO} + w_{RF})t] + \frac{1}{2}cos[(w_{LO} - w_{RF})t] \tag{2.2}$$

The high frequency term can then be removed with a low pass filter :

$$S = \frac{1}{2}cos[(w_{LO} - w_{RF})t] \tag{2.3}$$

The signal is then applied to a filter which only acept a bandwidth Δw$_{IF}$, so the range of accepted frequencies is w$_{IF}$-$\frac{1}{2}\Delta$w$_{IF}$ to w$_{IF}$+$\frac{1}{2}\Delta$w$_{IF}$, where ν_{IF} is the intermediate frequency. The signals which are accepted satisfy :

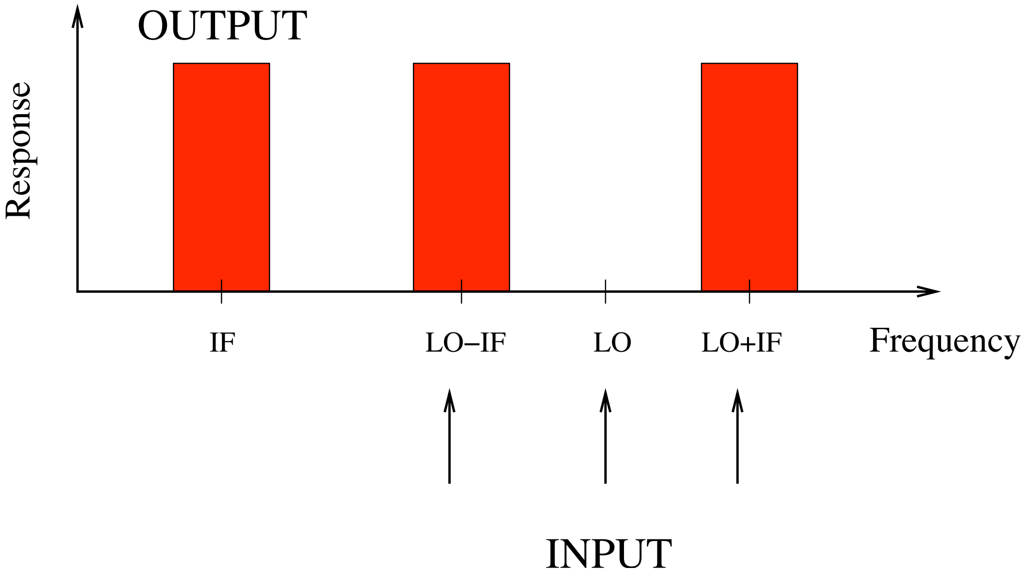
$$w_{IF} - \frac{1}{2}\Delta w_{IF} <\mid w_{LO} - w_{RF} \mid< w_{IF} + \frac{1}{2}\Delta w_{IF} \tag{2.4}$$

and the accepted RFs are :

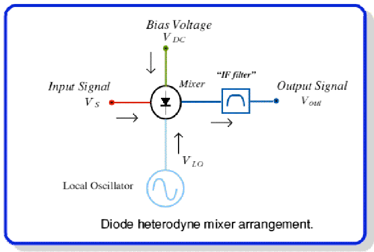
$$(w_{LO} - w_{IF}) - \frac{1}{2}\Delta w_{IF} < w_{LSB} < (w_{LO} - w_{IF}) + \frac{1}{2}\Delta w_{IF} \qquad (2.5)$$

$$(w_{LO} + w_{IF}) - \frac{1}{2}\Delta w_{IF} < w_{USB} < (w_{LO} + w_{IF}) + \frac{1}{2}\Delta w_{IF} \qquad (2.6)$$

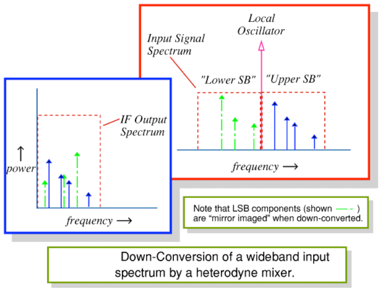
where LSB denotes the lower sideband, USB the upper sideband, and the LSB has frequencies in the opposite order. For $\nu \leq$ a few tens of GHz, the signal is applied to low noise amplifiers and then passed through a filter which admits only one sideband (single-sideband mixer). Fow $\nu \geq$ 100 GHz, it is difficult to make low-noise amplifiers, so both sidebands are accepted for weak signals (double-sideband mixer).



Consider an example where we have an input signal at a frequency of, say ν_S=50 GHz.



Diode heterodyne mixer arrangement.



Note that LSB components (shown — -) are "mirror imaged" when down-converted.

Down-Conversion of a wideband input spectrum by a heterodyne mixer.

This comes from a "distant" signal source, i.e. one which isn't a part of our measurement system. The signal is applied to the diode along with an output at, say, ν_L=49.999 GHz, from a Local Oscillator (LO), i.e. one which is part of our measurement system. The diode's non-linearity is said to mix these two signals to produce an output at the frequency, (ν_S-ν_L) = 1 MHz. This frequency is much lower than that of the original signal, hence it is much easier to amplify, filter, and measure its properties. The diode, local oscillator, and filter act together as a Heterodyne Receiver. Heterodyning is the process of beating together or Mixing two different frequencies to obtain an output at some other, related frequency. When used in this way the diode is called a Mixer Diode.

The heterodyne receiver is an example of a system which uses the technique called Frequency Conversion. An input at the frequency ν_S is converted to an output at (ν_S-ν_L). For obvious reasons this is also called Down Conversion. In this case the output filter selects an output frequency which is lower than either the signal or local oscillator frequency. Also, we could have used a filter which only passed frequencies around the Sum Frequency, (ν_S-ν_L). The heterodyne system would then perform Up Conversion on the input signal. In either case it is normal to refer to the filtered output from the mixer as the Intermediate Frequency output. This is because the output from the mixer and filter is often processed by other circuits before being reconverted into the output finally required.

Chapitre 3

Millimeter and submillimeter heterodyne technologies

Both Schottky diode and superconducting tunnel junction (Superconducting-Insulator-Superconducting = SIS) mixers could be used on the submillimeter heterodyne receivers. The Earth (or other planets) atmospheric research does not need as high a sensitivity, and uses Schottky diode mixers ; the astrophysic research needs the highest sensitivity, currently employs SIS mixers cooled at 4 Kelvin. Waveguide with horn and Quasi-optical mixer technologies are both employed up to 5THz.

3.1 Submillimeter Schottky diode mixers

For more than two decades the best uncooled heterodyne radiometers for use in the 100 GHz to 5 THz frequency range have been composed of waveguide or open structure mixers with whisker-contacted metal-semiconductor Schottky-barrier honeycomb diodes (a 4.5 THz open-structure mixer was developped at MPIFR-DLR for airborne experiment) In order to reduce the assembly cost and to improve the reliability and reproducibility of heterodyne receivers for the space missions throughout the millimeter and submillimeter wavelength bands, two major changes have been incorporated into current radiometer design. First, the whisker-contact honeycomb diode (used in SWAS, ODIN,...) have been replaced by planar diodes, mainly for subharmonically pumped mixers (SHP), for applications up to (or above) 600 GHz (MHS ; MIRO/ROSETTA ; EOS-MLS, MASTER-SOPRANO,...) ; second, the diode is integrated with the mixer circuitry (MMIC-like). An added benefit to this latter approach is the all planar photolithographic structure scalable to frequencies well beyond a THz (JPL, SHP mixer for EOS-MLS). A major goal is to advance the state-of-the-art in millimeter-wave with the planar-diode technology associated with micro-machined mixer structures (RAL) to the point at which it can be used readily at frequencies as high as 2.5 THz (PYRAMID, EOS-MLS,...). The Schottky diodes can be cooled to 70 or 20-30 K, increasing the performances, but work even at room temperature which is an advantage for several space applications.

3.2 Superconducting tunnel junctions and HEB mixers

In order to obtain ever higher sensitivity, shorter observation times and the use of smaller collecting surfaces, the submillimeter-wave astrophysics community has devoted much of their ressources towards the developpement of heterodyne radiometer front-ends based on superconducting mixers. The small area superconductor-insulator-superconductor (SIS) Nb tunnel junction offers the potential of near quantum limited sensitivity throughout the millimeter-wave bands up to 700 GHz and possibly at frequencies as high as 1.1 THz with normal metal tuning stub circuits (Al) or up to 1.4 THz by using NbTiN superconducting new material. The Supra-THz domain is recently achievable by using Hot Electron Bolometers heterodyne (HEB) mixers. The SIS and HEB mixers must be physically cooled to temperatures well below the superconduction transition temperature, (4 K or less). However, the requirement for a liquid helium ambient environment poses a significant limitation for remote, long lifetime space operation.

3.2.1 SIS mixers

Heterodyne front-end receiver at 420-440 GHz using SIS Nb junction with a classical tuning circuit for PRONAOS and for the PIROG 8 ballon borne experiment. An important part of the research in this field aims at developing receivers combining ultra wide bandwidths (around 30% relative or more) with ultra low-noise capabilities (a few times the quantum limit), with no mechanical tuning for space applications.

3.2.2 HEB mixers

Superconducting Hot Electron Bolometers becomes very promising mixing element for THz observations and it also shows good performances even below the gap frequency of Nb. Super-conducting HEB may go competitive with SIS junction at millimeter and submillimeter wavelengths since it provides several advantages compared to SIS mixers : smaller LO power, no need of external magnetic field to suppress Josephson current noise, relative ease to match into the antenna impedance due to its nearly resistive impedance, and no upper frequency limit. But there are some problems to be resolved for radioastronomical applications like relatively narrow IF bandwidth and elaboration of mixing theory on superconducting HEB.

3.3 LO technology

For millimetre and sub-millimetre wavelengths heterodyne receivers, the local oscillator (LO) is a critical element. The L.O. power needed for Schottky diodes or SIS junctions, is currently obtained by Gunn oscillators cascaded with frequency multipliers using whiskered varactor diodes. Local oscillator frequencies above 120GHz can generally not be generated directly by Gunn oscillators. In that case, the Gunn power is fed to a frequency multiplier, which is a non-linear device like the mixer, but based on non-linear capacitance, and optimized to produce a certain harmonic (x2,x4, x6) of the input frequency. The efficiency of the multiplication process is typically a few percent.

Chapitre 4

The Heterodyne Instrument For the Far Infrared (HIFI)

HIFI is the heterodyne instrument on the Herschel Space Observatory (HSO). As its name states it employs the heterodybe technique to provide high spectral resolution (R up to 10^7). It will be able to resolve the atomic, ionic, and molecular rotational lines in the submillimeter and far-infrared regions and probe dynamics, temperatures, densities, and abundances within a varirty of sources.

Direct detection with a high resolution spectrometer is very difficult within the submm and far-IR regime. Therefore, HIFI employs the heterodyne technique where the sky signal is mixed with an external signal close to the frequency of interest from a Local Oscillator. Then, the the mixing is done in a non-linear device, and the result is a signal at much lower frequency, but still containing all spectral information. This lower frequency is easier amplified and easier read-out.

In order to achieve the highest sensitivity, HIFI uses cryogenic mixers at a temperature less than 4 K. In the lowest 5 bands, so-called SIS mixers are used, whereas in its highest bands HEB mixers are favoured.

Amplification takes place right after, where the IF signal is detected (in double side-band) in a 4 GHz wide-band spectrometer (employing an Acousto-Optical Spectrometer) and in a high resolution autocorrelation spectrometer (HRS) in subbands within the same 4 GHz.

An overview of the intrument characteristics is given the the following table.

Band	1	2	3	4	5	6
Frequency range (GHz)	480-640	640-800	800-960	960-1120	1120-1250	1410-1910
Beamwidth ($''$)	39	30	25	21	19	13
DSB Receiver noise (K)	90	130	160	210	370	650