Lesson 5:
SODAR
(Sound Detection and Ranging)

Course: Laboratory of Atmospheric Remote Sensing
Laurea Magistrale in Atmospheric Science and Technology

Contents

SODAR

SODAR (**SOnic Detection And Ranging**) systems are used to remotely measure the vertical turbulence structure and the wind profile of the lower layer of the atmosphere.

SODAR systems are like **radar** (radio detection and ranging) systems except that sound waves rather than radio waves are used for detection.

A more familiar related term may be sonar, which stands for sound navigation ranging. Sonar systems detect the presence and location of objects submerged in water (e.g., submarines) by means of sonic waves reflected back to the source.
SODAR systems are similar except the medium is air instead of water and reflection is due to the scattering of sound by atmospheric turbulence.

SODAR

SODAR systems can be used in any application where the winds aloft or the atmospheric stability must be determined, particularly in cases where time and cost are of the essence.

Some typical applications include:

- atmospheric dispersion studies
- atmospheric circulation
- wind energy siting, wind shear warning
- emergency response wind monitoring
- sound transmission analyses
- microwave communications assessments
- aircraft vortex monitoring

SODAR

SODAR permits to correlate intense acoustic echoes in the presence of atmospheric turbulence.

Atmospheric turbulence is generated by both thermal and mechanical forces:

- thermal turbulence results from temperature differences, or gradients, in the atmosphere
- mechanical turbulence is caused by air movement over the natural or man-made obstacles that produce the "roughness" of the earth's surface. Turbulence from either source results in turbulent air parcels or ***eddies*** of varying sizes.

The basic mechanism for the propagation of the acoustic wave is the exchange continuous between kinetic energy of the fluid and stored potential energy in compression.

SODAR

The SODAR sends into the atmosphere trains of short but powerful acoustic tones.

Return "echoes" are acquired, analyzed and recorded in a similar way to a sonar.
To reduce the environmental acoustic noise, which could obscure the echo, the antenna is usually coated with sound-absorbing screens.

- ✓ Since the speed of sound is less than that of electromagnetic waves, the equipment used is simple to make and inexpensive.
- ✓ The techniques used for data analysis do not require expensive and/or sophisticated equipment.

SODAR

The motion of the atmosphere is the result of general wind flow and **turbulence** (the irregular fluctuations of small-scale horizontal and vertical wind currents).

Reflactive index → depends on air temperature, relative humidity

↓

When an acoustic (sound) pulse transmitted through the atmosphere meets an eddy, its energy is scattered in all directions. Although different scattering patterns result from thermal and mechanical turbulence, some of the acoustic energy is always reflected back towards the sound source.

That **backscattered energy** (i.e. atmospheric echo) contains information on inhomogeneities in temperature, and to a lesser extent, in humidity.

SODAR

Advantages:

- ✓ low labor cost for measurements
- ✓ continuous operation, much more reliable and durable
- ✓ continuous measurement
- ✓ do not need any yearly check up or calibration
- ✓ fast installation
- ✓ maintenance is minimal: cleaning the antenna from leaves and debris once in a while
- ✓ easy to transport from one place to another place
- ✓ is sensitive to small scale temperature turbulence

SODAR

Disadvantages:

- make some noise
- the sound signal is highly attenuated in the atmosphere. The attenuation of the sound wave increases as the frequency increases
- cannot operate in areas where the noise level is high
- precision (although better than radars) is slightly lower than the precision of the best Lidars
- they cannot operate very close to large obstacles while the Lidars can

SODAR

The SODAR uses thermal fluctuations as a tracer.

Since the sound is very fast, the beam action hardly exceeds one kilometer.

Visualization of phenomena that produce or are accompanied by temperature fluctuations in the first hundred meters.

- ✓ **thermals** that develop in a convective boundary layer and, in the presence of a sufficiently intense inversion layer above the thermals, also displays the convective boundary layer and, in the presence of a sufficiently intense **inversion layer** if within the radius of action of the instrument.
- ✓ in the presence of thermal strains and shear wind, atmospheric stratifications and their movements, generally associated to **gravity waves**, can be observed.

Acoustic wave propagation in turbulent atmosphere (1)

The SODAR periodically sends into the atmosphere a train of acoustic waves with a frequency generally between 1 and 3 kHz (3-6 kHz for mini sodars).

Disregarding the contribution of humidity variation, the theory of sound diffusion in the case of homogeneous and isotropic turbulence provides the following expression for the differential acoustic cross section per unit of volume and per unit of solid angle:

$$\eta(\vartheta) = \frac{1}{8} k^4 cos^2\vartheta (\frac{\Phi_T(x)}{T_0} + \frac{cos^2(\vartheta/2) E(x)}{\pi c^2 x^2})$$

where:

Φ is the angle, in the diffusing volume, between the axis of the transmitted beam and the diffusion direction;

x is the wave number that satisfies the Bragg conditions for diffusion, i.e. 2ksinϑ/2 (in particular, for diffusion at 180 ° only the dynamics of $\lambda/2$ contribute constructively to forming the backscattered wave)

T_0 is the average temperature in the diffusing volume

c is the sound speed

$k = 2\pi/\lambda$ is the acoustic wave number

$E(x)$ and $\Phi_T(x)$ are the three-dimensional spectral density of power of velocity fluctuations of wind and temperature, relative to the wave number x

Acoustic wave propagation in turbulent atmosphere (2)

$E(x)$ and $\Phi(x)$ characterize the field of thermal and mechanical inhomogeneities and are connected to the structure functions $D_T(\boldsymbol{r})$ and $D_V(\boldsymbol{r})$:

$$D_T(\boldsymbol{r}) = \langle [T(\boldsymbol{p}+\boldsymbol{r}) - T(\boldsymbol{p})]^2 \rangle$$

$$D_V(\boldsymbol{r}) = \langle [V(\boldsymbol{p}+\boldsymbol{r}) - V(\boldsymbol{p})]^2 \rangle$$

where:

<> indicates the ensemble average

$\boldsymbol{p}$ is the point in which the fuction is computed

$\boldsymbol{r}$ is the distance between sensors

Acoustic wave propagation in turbulent atmosphere (3)

If we consider the atmospheric wave numbers, viscosity is negligible and we have:

$$D_T(\boldsymbol{r}) = C_T^2 r^{2/3}$$

$$D_V(\boldsymbol{r}) = C_V^2 r^{2/3}$$

where

r is the magnitude of $\boldsymbol{r}$

C_T^2 and C_V^2 are parameters based on temperature and velocity

So, in the inertial subrange, fluctuations depend only on the measurement point. With these hypotesis, the spectral densities read:

$$E(x) = 0{,}76 v^2 x^{-5/3} \qquad \text{and} \qquad \Phi(x) = 0{,}033 C_T^2 x^{-11/3}$$

Acoustic wave propagation in turbulent atmosphere (4)

$$\eta(\vartheta) = \frac{1}{8} k^4 x^{-11/3} cos^2\vartheta \left(\frac{0{,}033 C_T^2}{T_0} + \frac{cos^2 0{,}76 C_V^2}{\pi c^2} \right)$$

- The diffused acoustic energy is the sum of two terms, one due to wind fluctuations, the other due to temperature fluctuations.
- Both terms depends on $cos^2\vartheta$, it means that there is no diffusion at 90 ° angles.
- The term linked to mechanical fluctuations includes a factor $cos^2\vartheta/2$, so there is not diffusion at 180° angles.

The 180° diffusion (backscattering) is due only to the contribution of thermal fluctuations. For other angles, it is also possible to receive a contribution linked to mechanical fluctuations.

Acoustic wave propagation in turbulent atmosphere (5)

The most commonly used SODAR systems use the same antenna to emit acoustic tones and receive echoes.

In this configuration, which is called **monostatic**, the echo has its origin in the thermal fluctuations that the train of acoustic waves encounters during its propagation.

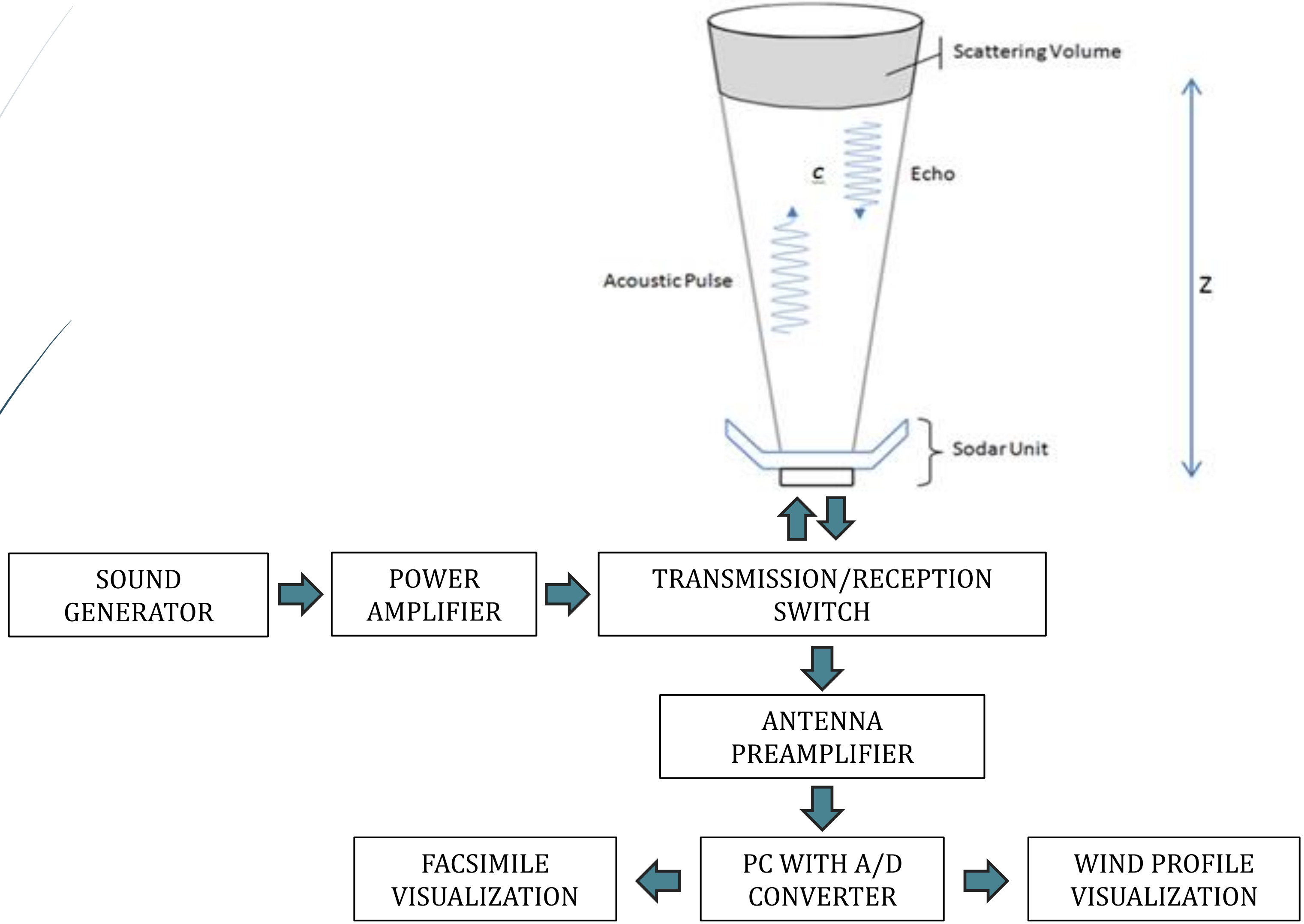
The equation describing the acoustic diffusion becomes in this case:

$$\eta(180°) = 0{,}004k^{1/3}\frac{C_T^2}{T_0}$$

The received echo is due to the existence of phenomena that give rise to, or are accompanied by, temperature fluctuations in a range of wave numbers centered on 2k (to satisfy the Bragg conditions for diffusion), where the width of the interval is determined by the truncation of the sound pulse.

SODAR – Working principle (1)

Simplified scheme of a monostatic acoustic probe, including essential components.



SODAR – Working principle (2)

1. An acoustic tone of 50 - 300 ms duration is amplified and emitted. The repetition rate depends on the maximum altitude you want to reach.
2. The receiving part of the apparatus is protected during the emission by a transmission-reception switch which opens the reception ports only when the transmission of the tone is completed and the oscillation of the transducer membrane acoustic has attenuated.
3. The signal containing the echo, which is received by the antenna first from the lower layers, hence from ever greater levels, is pre-amplified to reduce the influence of electronic noise along the transmission lines.
4. The signal is amplified linearly to take into account the spherical divergence of the beam and is sampled.

After each emission the signal will be available as a function of time, from which to extract the intensity profile (from the envelope) and the radial wind profile (from the frequency analysis).

SODAR – Configurations (1)

Basing on the equation

$$\eta(\vartheta) = \frac{1}{8}k^4 cos^2\vartheta(\frac{\Phi_T(x)}{T_0} + \frac{cos^2(\vartheta/2)E(x)}{\pi c^2 x^2})$$

that describes the diffusion in the atmosphere of the acoustic wave, we have seen that the energy is given by the mechanical fluctuations and temperature fluctuations.
The intensity of the two terms depends on the angle of diffusion. If the angle is equal to 180°, the mechanical fluctuations can be neglected.

Basing on the contribution of the mechanical fluctuations we have:

- **Monostatic SODAR**:

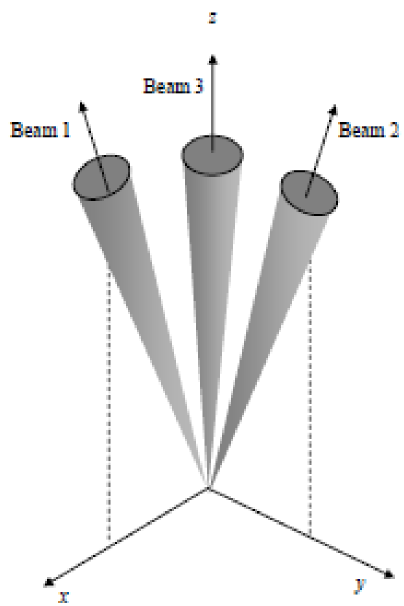
Emitter/receptor are the same (or a closely spaced) speaker or set of speakers

- **Bistatic SODAR**:

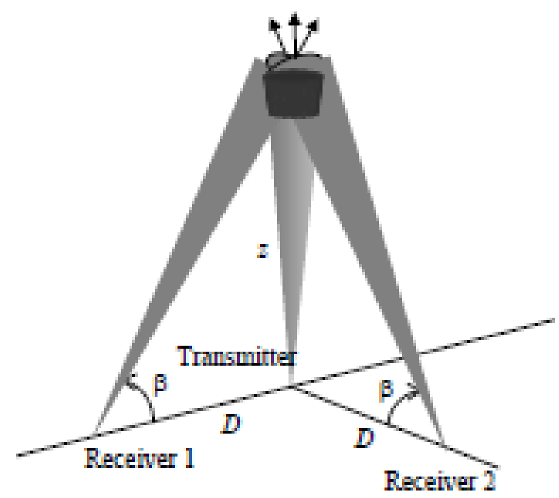
Emitter and receptor speaker (or speakers) are separated at a distance.

SODAR – Configurations (2)

Monostatic SODAR:



Bistatic SODAR:



SODAR – Signal analysis (1)

The delay time t with which the signal is received determines the altitude z of the echo

$$z = c\ t/2$$

c = 340 m/s = speed of sound (temperature function)

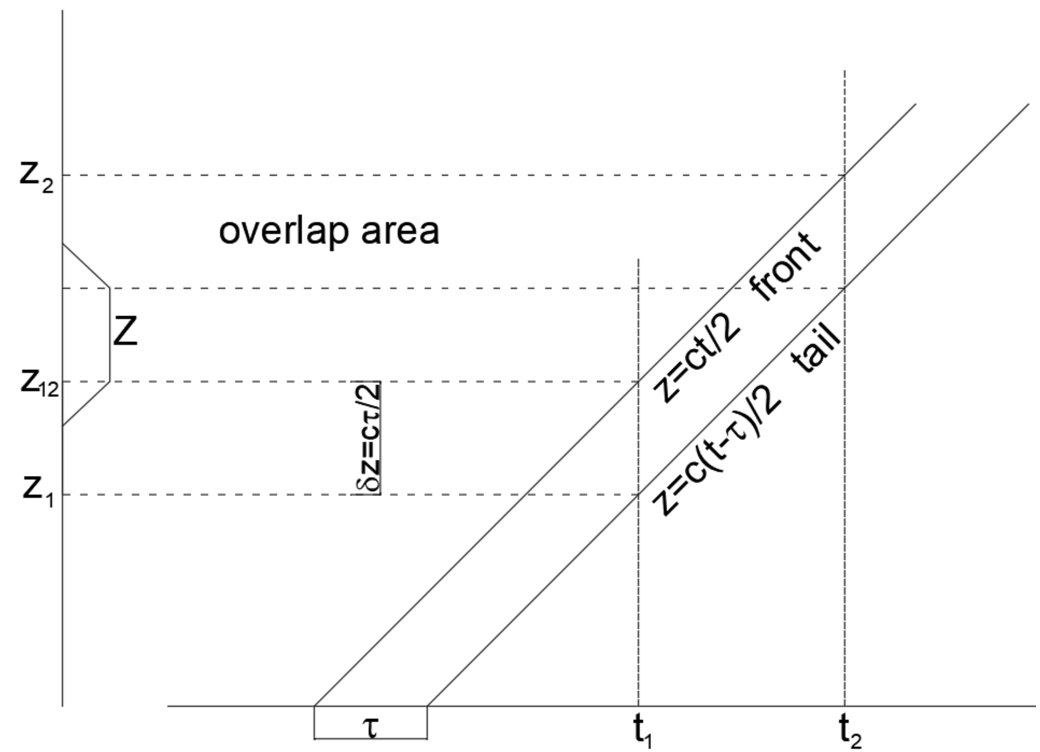
The temporal length of the signal on which the harmonic analysis is made determines, for each altitude, the thickness of the layer to which the radial speed is associated.
The time length τ of the emitted acoustic burst determines the vertical resolution of the instrument.

Resolution $\Delta z = c\tau/2$

The theoretical maximum height is determined by burst repetition rate.
The minimum height (dark zone) is a function of the membrane damping time.

SODAR – Signal analysis (2)

At t_1, the antenna simultaneously records the echoes coming from $z_1 = (c/2)(t_1 - \tau)$ and $z_{12} = (c/2)t_1$
where τ is the acoustic tone length.
It means that we have an indetermination on the height of the echo equal to $\delta z = c\tau/2$.
The results of the echo analysis between t_1 and t_2 will be associated with the interval $Z = (c/4)(t_1 + t_2) - \tau c/2$



SODAR – Example of analysis

<u>Echo height:</u>
If t = *4 s*:
z = 340**4*/2= 680 m

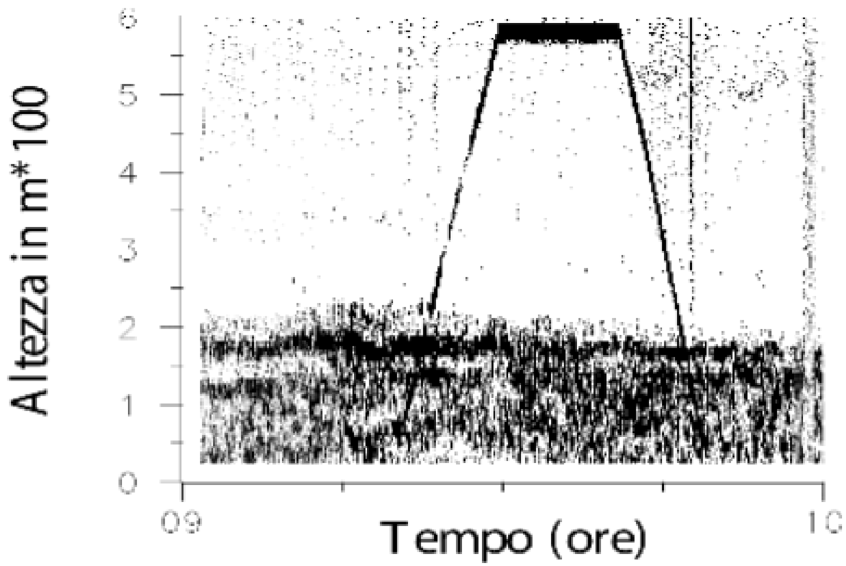
<u>Layer thickness:</u>
If signal duration is *160 ms*
Z = *0,16**340/2 = **27 m**

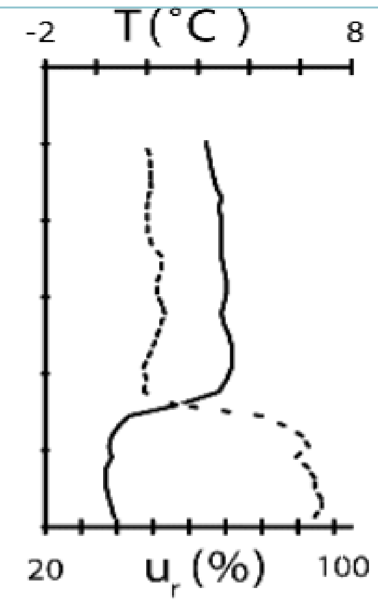
<u>Vertical resolution data:</u>
If burst duration is *100 ms*
*0,1**c/2 = **17 m**

<u>Theoretical maximum height:</u>
If rate emission burst is *6 s*
6 *c/2 = **1020 m**

<u>Minimum height:</u>
If burst duration is *100 ms*
*0,1**170 = **17 m**

SODAR – Examples of facsimile

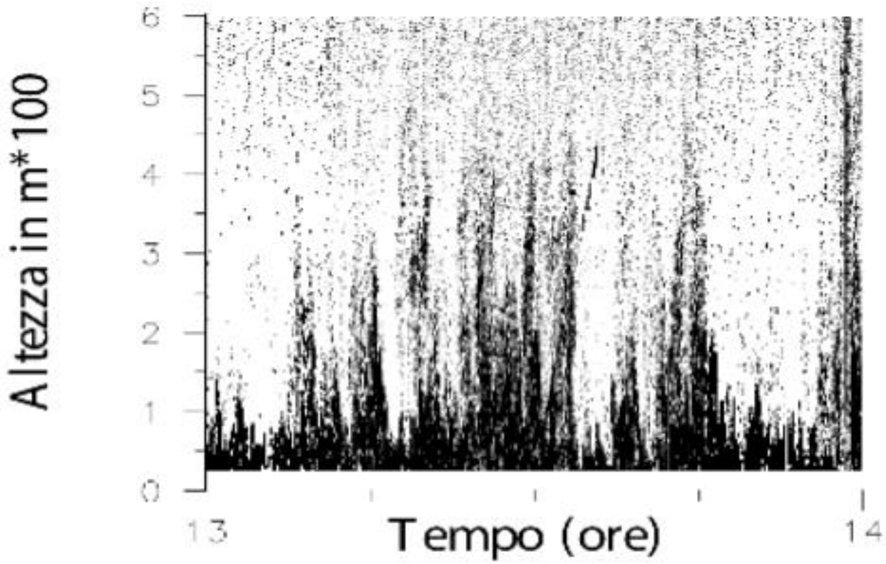




Echo SODAR facsimile related to atmospheric stability.

On the right, we have the temperature vertical profile (continuous line) and the relative humidity profile (dashed line) obtained using a weather balloon. The vertical black lines in the facsimile identify the ascending/descending phase of the balloon.

SODAR – Examples of facsimile



Echo SODAR facsimile related to atmospheric instability.

On the right, we have the temperature vertical profile (continuous line) and the relative humidity profile (dashed line) obtained using a weather balloon. The vertical black lines in the facsimile identify the ascending/descending phase of the balloon.

SODAR – Wind velocity

The radial wind speed for a monostatic system is calculated from the Doppler drift of the echo with respect to the carrier frequency f_0.

From the radial speed along the axis of each antenna we have the wind speed components v_x, v_y, v_z.

Δf is the frequency shift due to the Doppler shift.

$$V \cong (c_0/2)(\Delta f/f_0)$$

where $\Delta f = f_0 - f$

If Δf<0 ⟹ negative wind speed

If Δf>0 ⟹ positive wind speed

$$V_x = -V_1 \frac{1}{sin\theta} + V_3 cotg\theta$$

$$V_y = -V_2 \frac{1}{sin\theta} + V_3 cotg\theta$$

$$V_z = V_3$$

SODAR – Applications (1)

Thermal structure of the atmosphere

- ❖ Atmospheric instability
- ❖ Thermal stability
- ❖ Waves
- ❖ Forced convection

Atmospheric dynamic

- ❖ Sea/land breeze regime
- ❖ Fronts convergence
- ❖ Night jet
- ❖ Internal waves

SODAR – Applications (2)

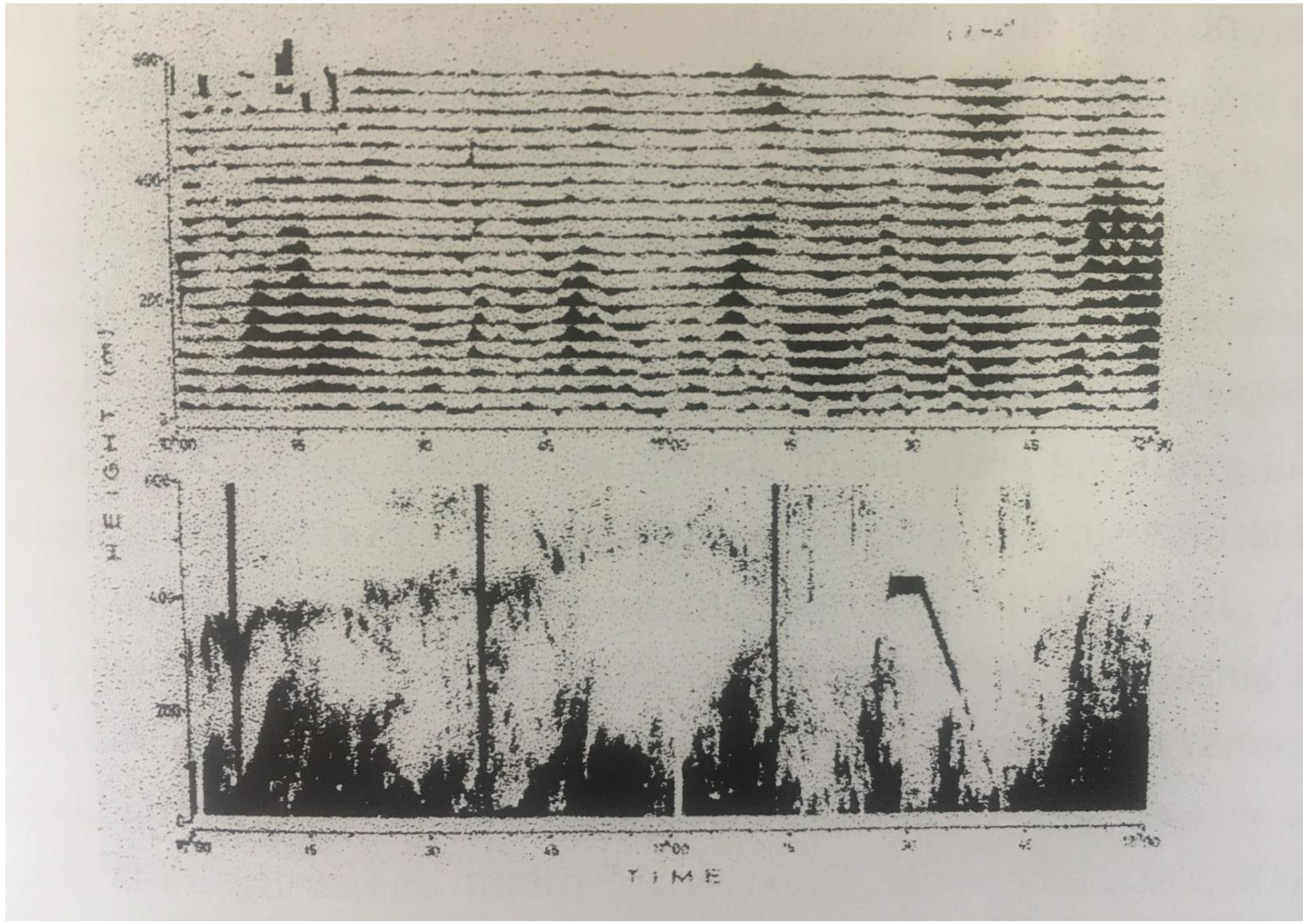
1. Atmospheric instability

Thermals, or convective currents, are periodic vertical structures that can be recorded during the day in the presence of solar radiation. From the surface layer, the air heated by the ground rises as thermal insulations that can trigger thermal families with an average life of 10-15 minutes.

The facsimile displays the wind carried through the acoustic beam of the wave. As a result, thermals can be deformed due to the underlying wind. The vertical development of the thermals, and therefore the thickness of the mixed layer, depends on the surface heating and the temperature in the upper layers.

SODAR – Applications (3)

1. **Atmospheric instability**



SODAR – Applications (4)

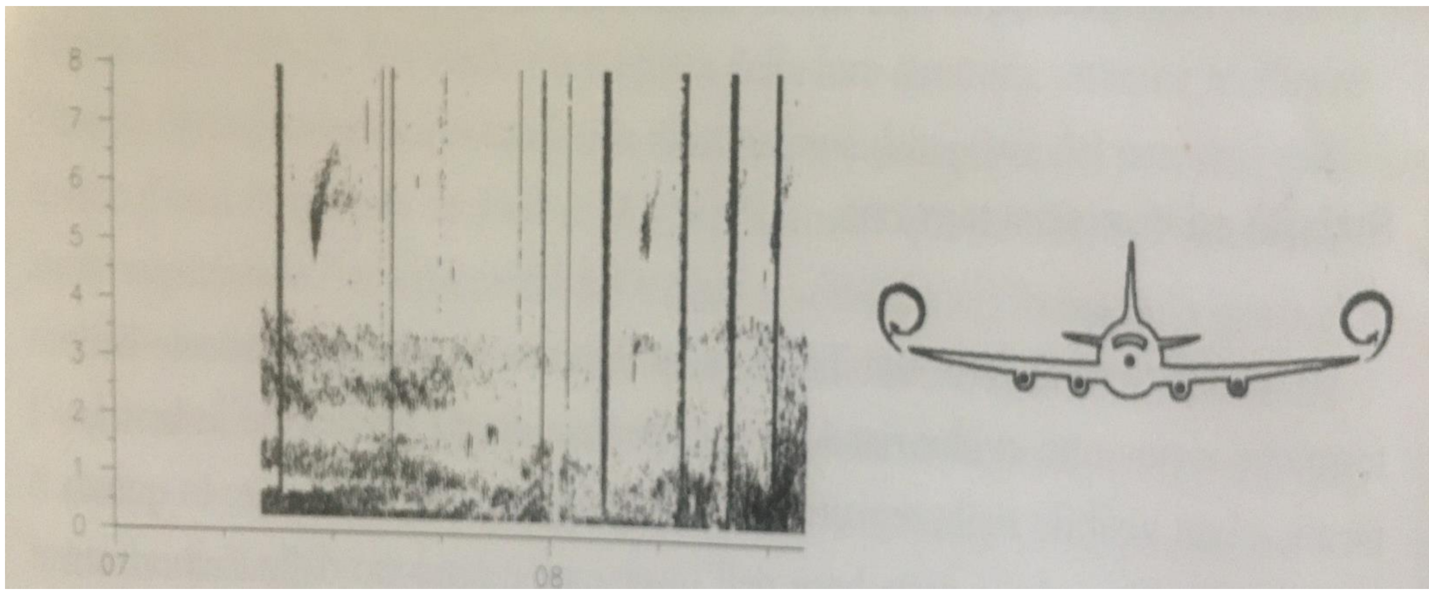
2. Atmospheric stability and thermal inversion

In the case of strong stability the facsimile shows the basis of the inversion produced by the fluctuations given by the interaction of the air that rises from the bottom and the warmer air that is at the top.

This is one of the few cases in which the facsimile allows the identification with certainty the height of the mixed layer.

SODAR – Applications (3)

2. **Atmospheric stability and thermal inversion**



SODAR – Applications (4)

3. Microfronts

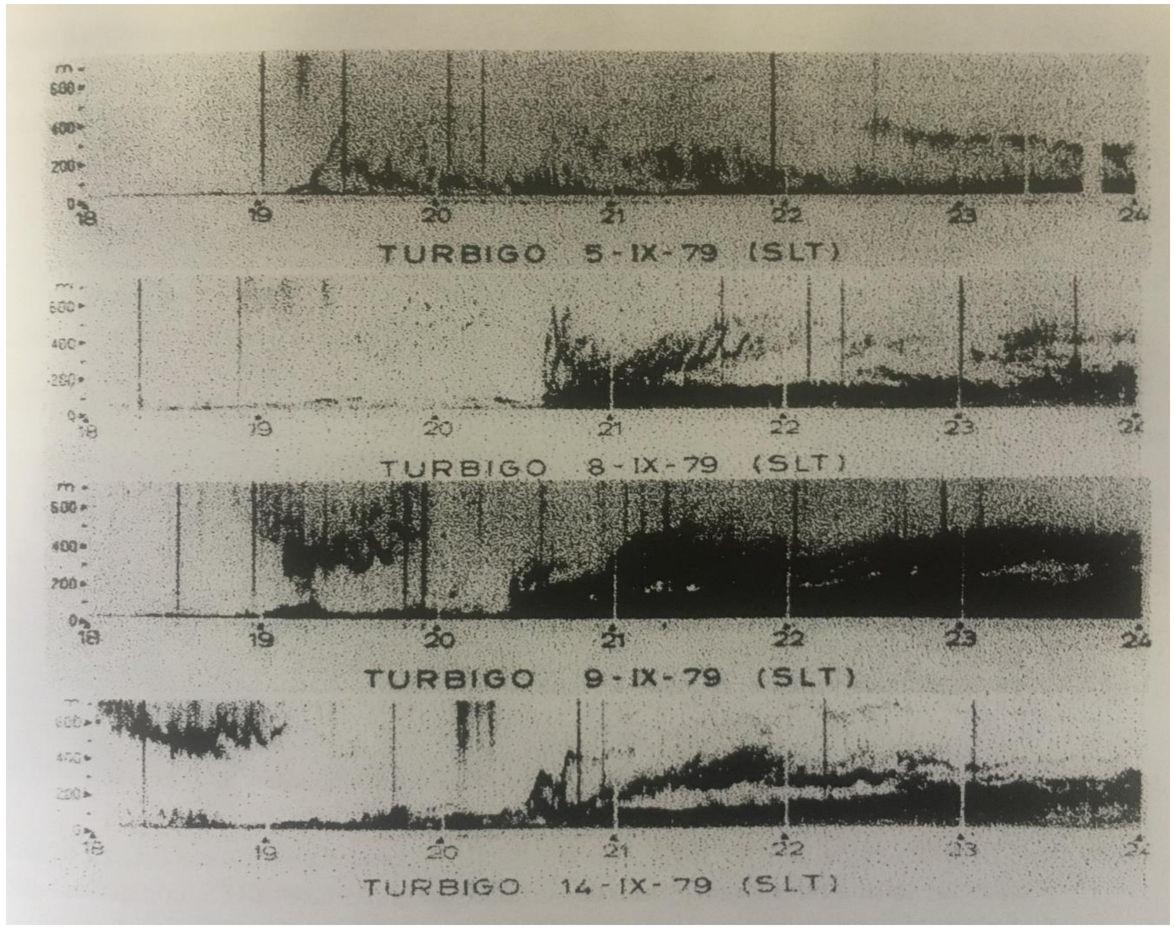
Microfronts lead to unpredictable sharp changes of temperature and wind direction shifts.

The different degree of heating/cooling of adjacent surfaces leads to the formation of adjoining air masses with different temperatures (and therefore different densities).

The horizontal pressure gradient causes the movement of cooler air masses towards the areas occupied by warmer air masses. In the initial stages of this shift, you can see the air front moving.

SODAR – Applications (5)

3. Microfronts



SODAR – Micrometeorology (1)

Computation of the **TKE balance equation** from SODAR data:

$$\frac{\partial e}{\partial t} = -\overline{uw}\frac{\partial U}{\partial z} + \frac{g}{\Theta}\overline{w\vartheta} - \frac{\partial}{\partial z}\overline{(we)} - \varepsilon - \frac{\partial}{\partial z}\overline{(\frac{wp}{\rho_0})}$$

$e = 0{,}5 * (w^2 + u^2 + v^2)$ represents TKE per mass unit

u, v, w are the fluctuations of wind along the mean wind, spanwise and vertical direction, respectively

Θ, ϑ are the fluctuations of potential temperature and its mean value, respectively

p is the pressure fluctuations

U is the mean velocity along the wind direction

ε is the viscosity dissipation

SODAR – Micrometeorology (2)

$$\frac{\partial e}{\partial t} = -\overline{uw}\frac{\partial U}{\partial z} + \frac{g}{\Theta}\overline{w\vartheta} - \frac{\partial}{\partial z}\overline{(we)} - \varepsilon - \frac{\partial}{\partial z}(\frac{\overline{wp}}{\rho_0})$$

(I) (II) (III) (IV) (V) (VI)

(I) TKE variation in time

(II) TKE production due to the vertical wind gradient

(III) TKE production due to thermal effects

(IV) TKE vertical transport

(V) Viscous dissipation

(VI) Redistribution of TKE due to pressure variations

In steady conditions (I) is equal to zero.

If you can consider the case of well-defined convection, the vertical wind gradient is negligible, so (II) is equal to zero.

Other terms can be obatained starting from SODAR data.

SODAR – Micrometeorology (3)

$$\frac{\partial e}{\partial t} = -\overline{uw}\frac{\partial U}{\partial z} + \frac{g}{\Theta}\overline{w\vartheta} - \frac{\partial}{\partial z}\overline{(we)} - \varepsilon - \frac{\partial}{\partial z}(\frac{\overline{wp}}{\rho_0})$$

(III) (IV)

(III) TKE production due to thermal effects

$$\frac{\sigma_w^3}{z} \approx \beta \frac{g\overline{w\vartheta}}{\Theta} \quad \Rightarrow \quad w_* = (\frac{g\overline{w\vartheta}}{\Theta} z_i)^{1/3}$$

(IV) TKE vertical transport

From experimental data: $\overline{w(u^2 + w^2)} = (0{,}7 - 0{,}78\frac{z}{z_i})\overline{w^3}$

$$\Downarrow$$

$$\overline{we} = \frac{1}{2}\overline{w(u^2 + v^2 + w^2)} = \frac{1}{2}\overline{w(u^2 + v^2) + w^3} \approx \frac{1}{2}(1{,}7 - 0{,}78\frac{Z}{Z_i})\overline{w^3}$$

SODAR – Micrometeorology (4)

$$\frac{\partial e}{\partial t} = -\overline{uw}\frac{\partial U}{\partial z} + \frac{g}{\Theta}\overline{w\vartheta} - \frac{\partial}{\partial z}\overline{(we)} - \varepsilon - \frac{\partial}{\partial z}(\frac{\overline{wp}}{\rho_0})$$

(V) (VI)

(V) Viscous dissipation

The inertial subrange of the power spectrum of vertical velocity fluctuations can be parameterized in terms of ε as follows:

$$P(f) = 0{,}20(\varepsilon U)^{2/3} f^{-5/3}$$

where f is the frequency.

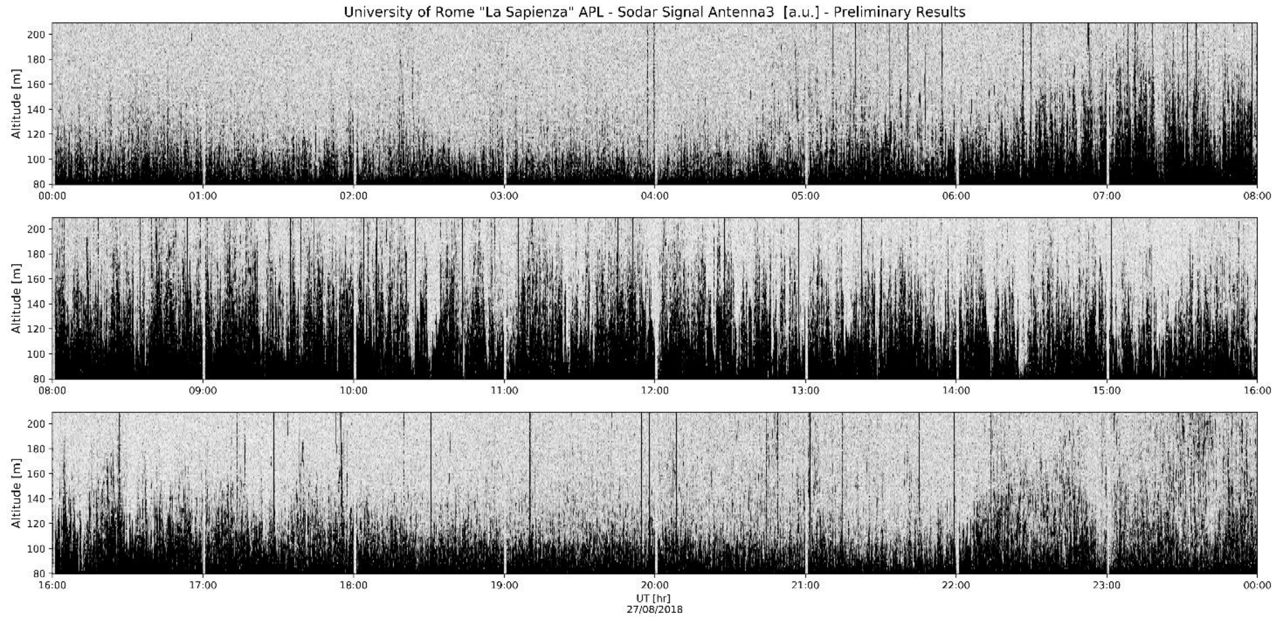
We can obtain:

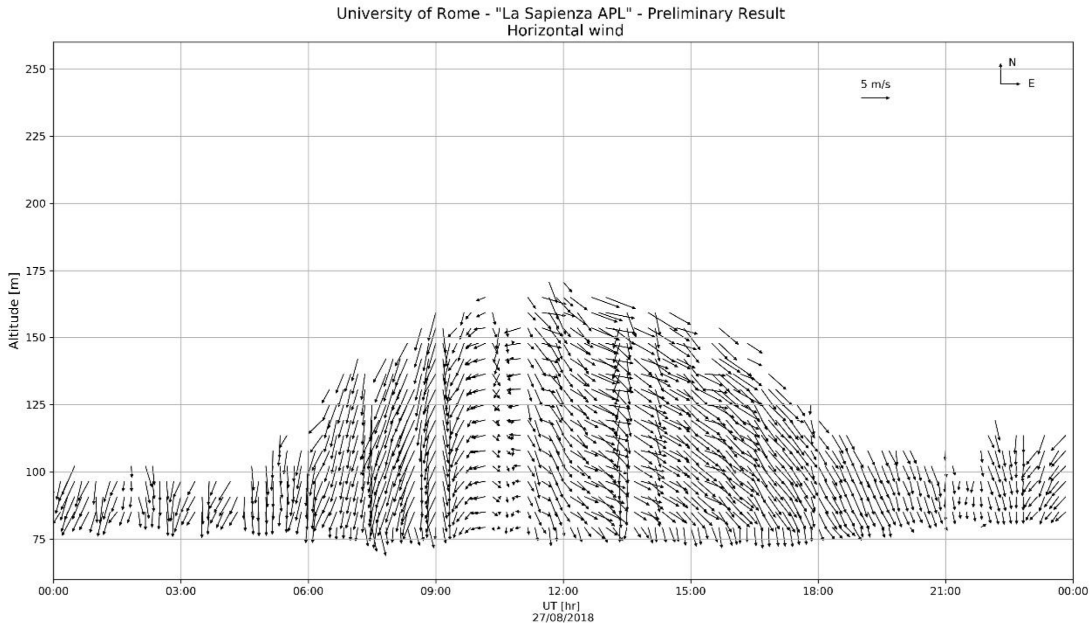
$$\varepsilon = 11{,}2 U^{-1}[P(f)]^{3/2} f^{5/2}$$

(VI) Redistribution of TKE due to pressure variations

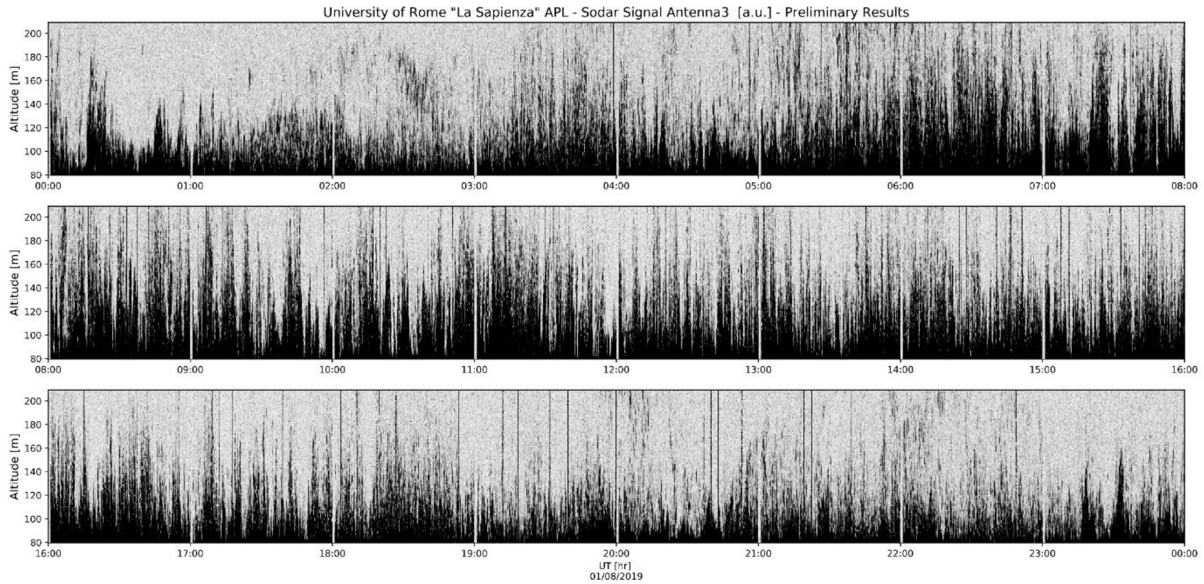
The pressure fluctuations are very weak in the atmosphere (0,01-0,05 mb). It is typically obtained as a subtraction from the other terms of the equation.

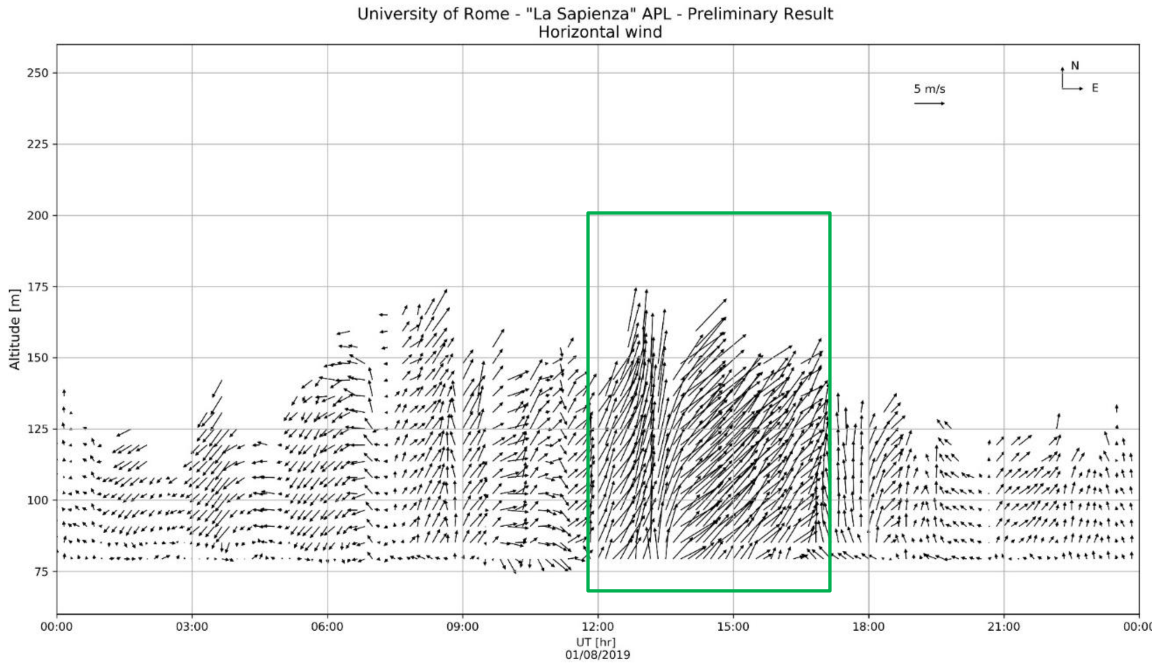
Examples: synoptic wind



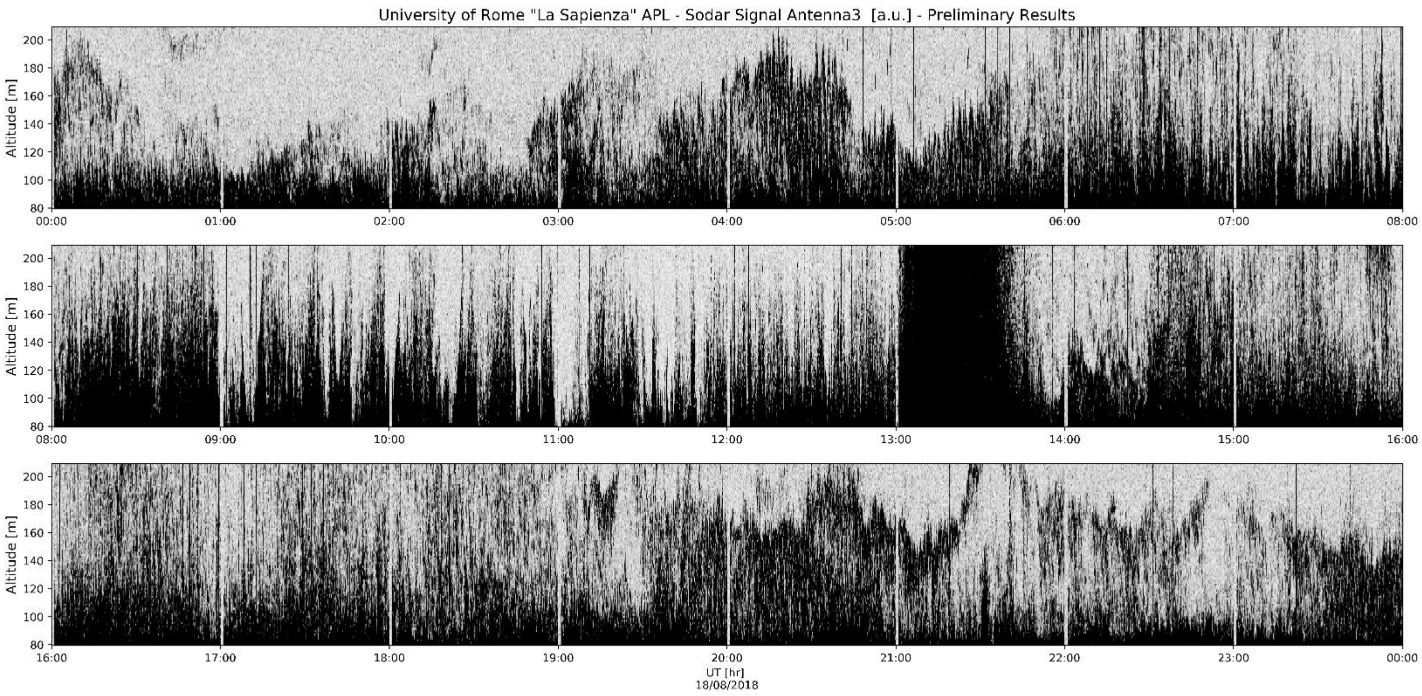


Examples: breeze regime

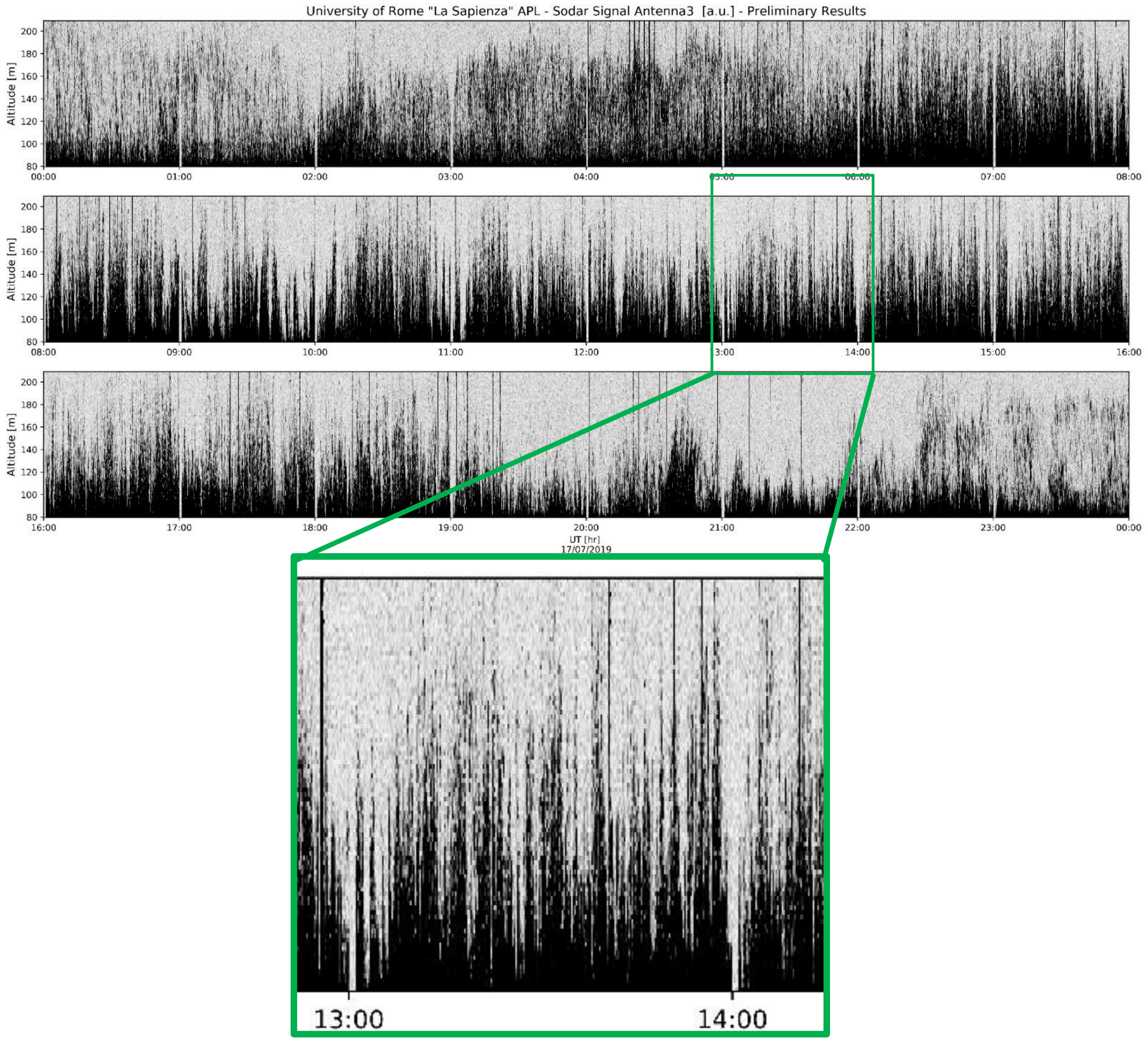




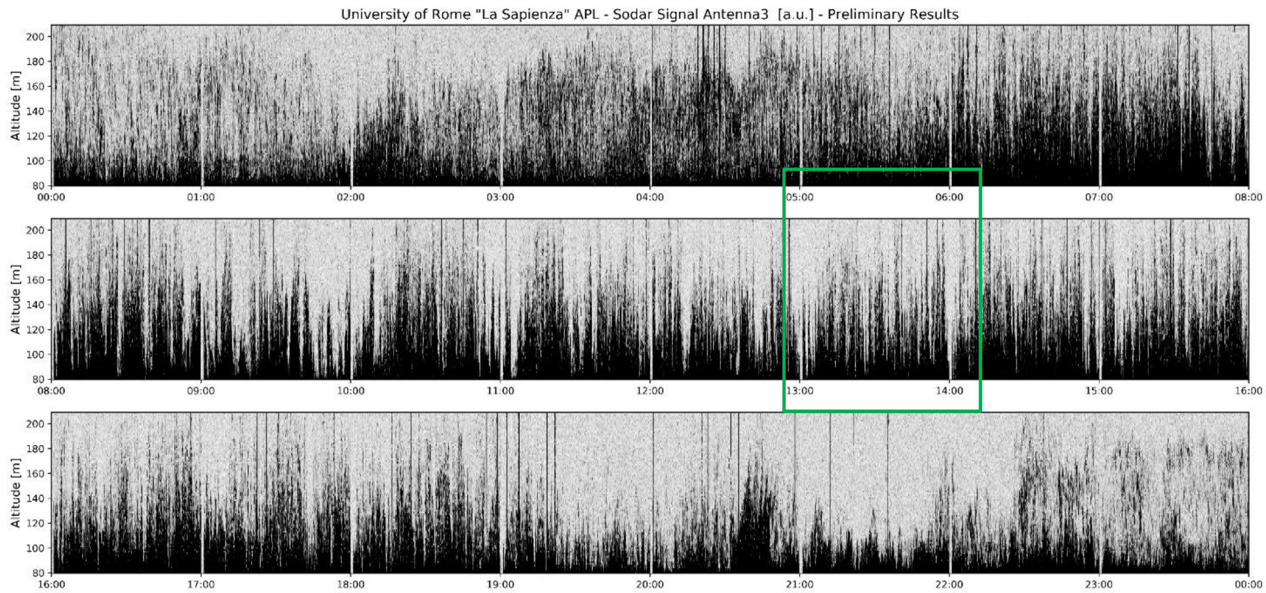
Examples: rain

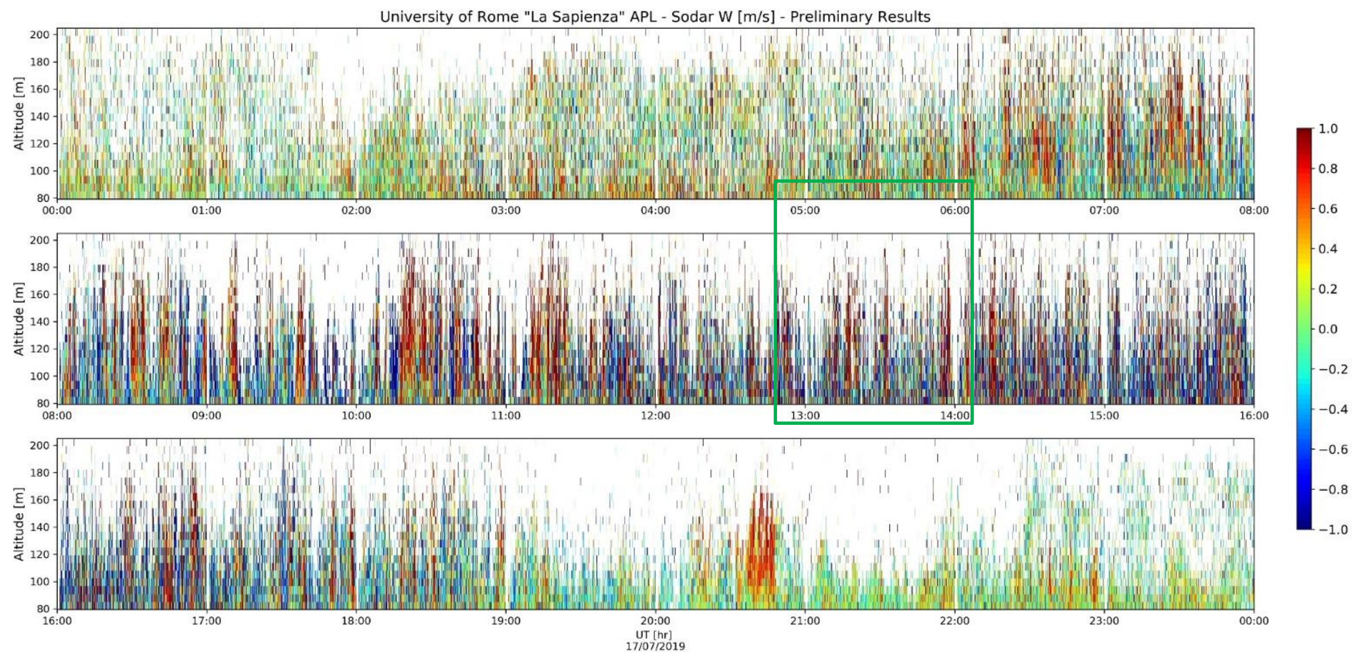


Examples: thermals structures



Examples: Thermals structures





Examples: Thermals structures