vers. 08

The amazing journey through an opportunistic satellite sensing system

From the "*bad-looking*" raw data to the "*handsome*" precipitation estimate

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Acknowledgments

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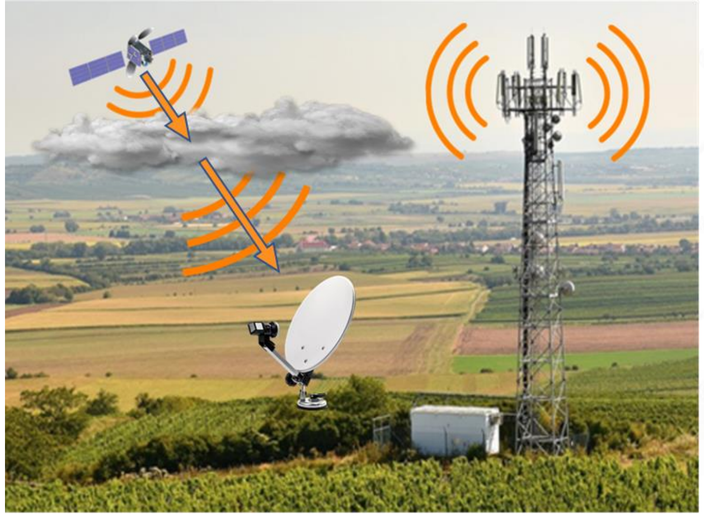
- Attilio Vaccaro (MBI, Pisa) and the whole teams of the NEFOCAST and INSIDERAIN projects.
- Roberto Nebuloni (CNR, Milan) and the whole Italian team within Opensense.

- **Integrated Sensing and Communication (ISAC):** technological concept that denotes the **symbiosis** between sensing and communication:
  - it enables **hardware & spectrum reuse ("for free") between sensing & communication functions**;
  - it enhances features such as location awareness and movement detection, and boosts efficiency and capacity;
  - as such, it has been identified as a novel feature of **6G and next-generation networks.**
- According to the International Telecommunication Union (ITU) Report ITU-R M.2516-0 "*Towards 2030*": ***Communication systems can support sensing services at radio level through the concept of "network as a sensor"***.



- **Pre-existing** communication infrastructures, either terrestrial or satellite-based, are sources of **microwave (MW) signals** that can be exploited for **Opportunistic Sensing (OS) of rain**.

Rain attenuation in MW communication links

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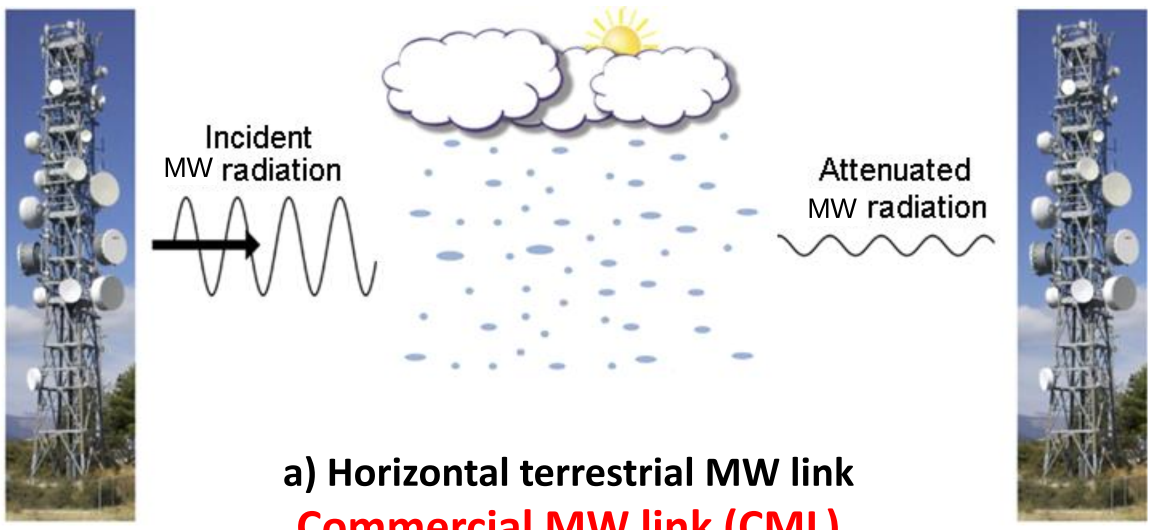
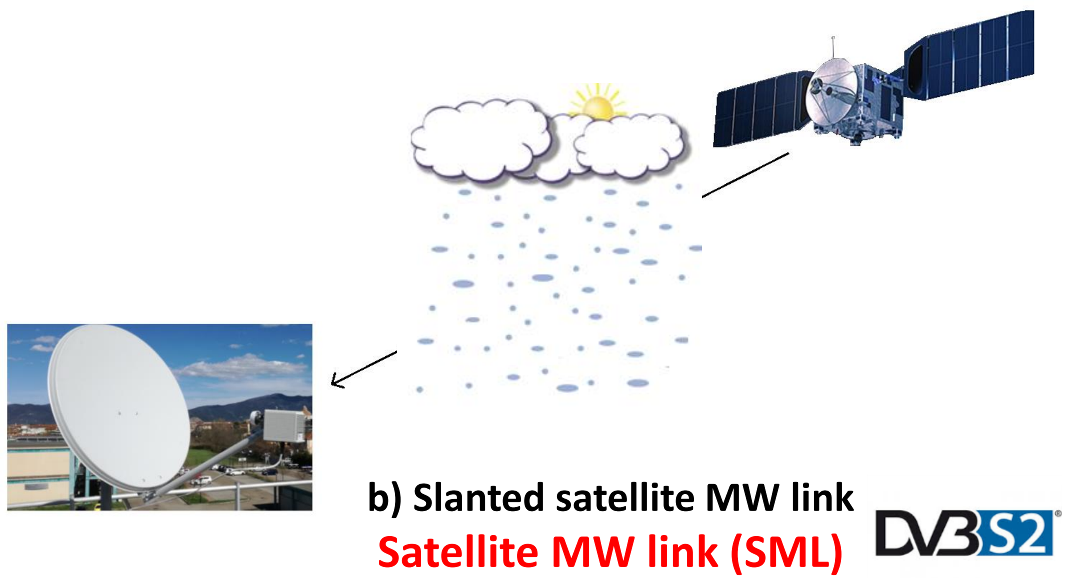
- Rain introduces additional attenuation on microwave (MW) communication links,
  due to signal reflection, scattering and absorption caused by raindrops (significant effects for f > 3 GHz).
- Both terrestrial and satellite MW communication links are affected by rain:
  a) backhaul connections of **commercial cellular networks**, via tower-to-tower horizontal paths;
  b) downlink of **direct-to-home (DTH) satellite broadcasting**, via satellite-to-ground slanted paths.



a) Horizontal terrestrial MW link
Commercial MW link (CML)



b) Slanted satellite MW link
Satellite MW link (SML)

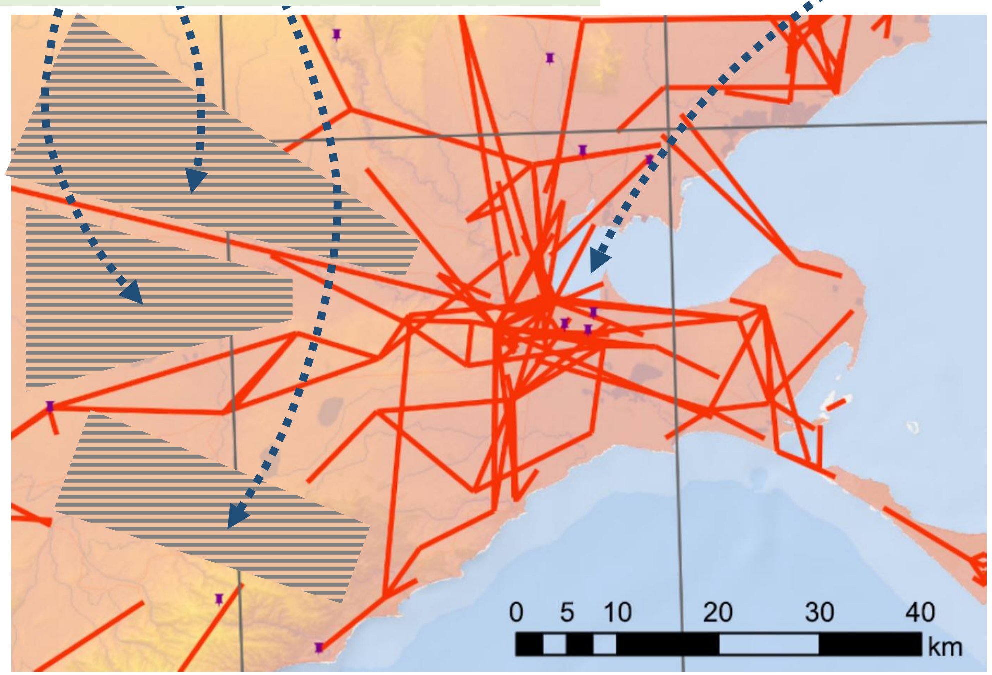
- **Opportunistic estimation of rainfall intensity** relies on **real-time measurements**, made at the receiver site, of an RF signal metric denoted as **Received Signal Level (RSL)**.

Limitations of CML-based opportunistic rain sensing

- For CMLs, however, access to **RSL** data requires the **authorization of the network operator** and **the payment of a fee**.
- Also, ground coverage of the CML mesh is non uniform: **coverage gaps, especially in rural areas.**
- **It is not possible to add new links to the mesh**, wherever necessary.

coverage gaps due to sparse CML in suburban/rural areas

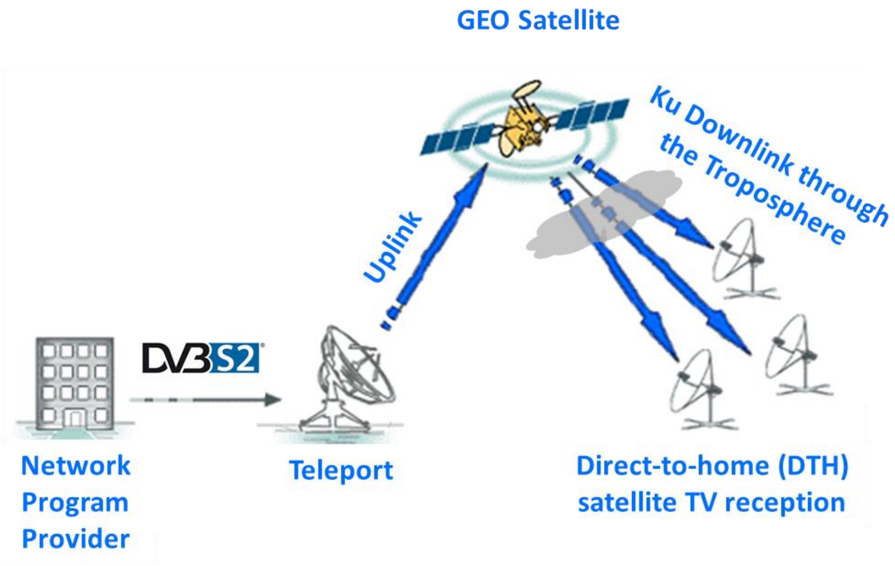
dense CML mesh in urban area

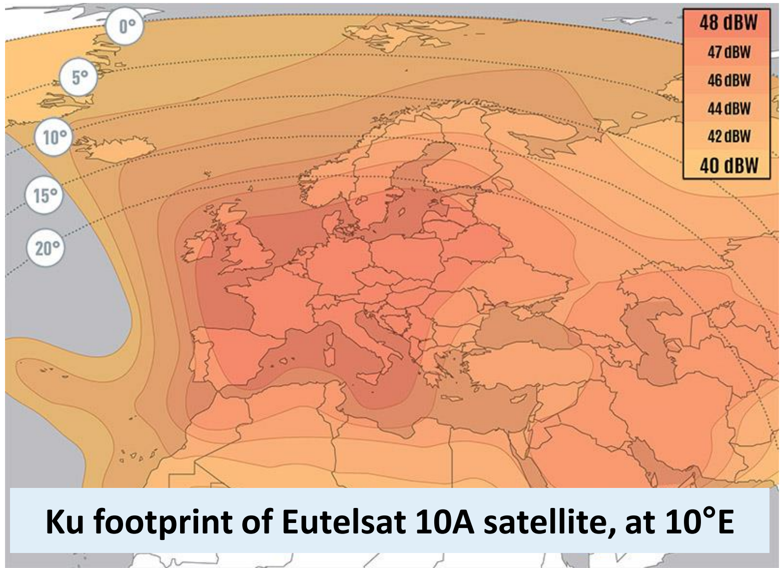


Mesh of CMLs in the area of Melbourne (AUS)

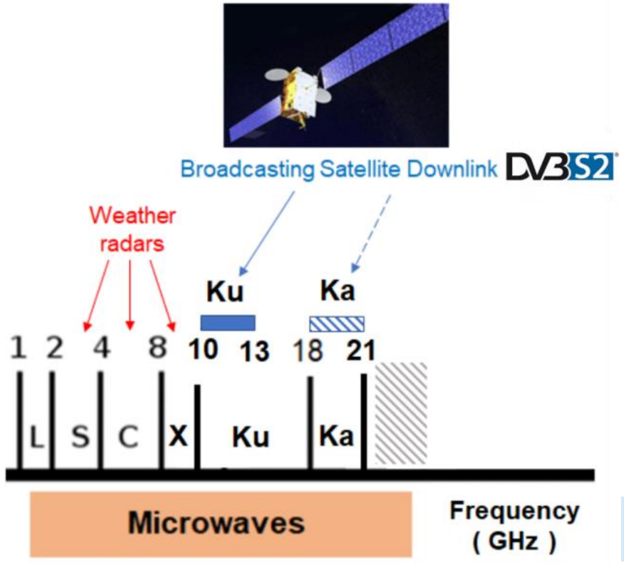
Hereafter, we will focus on the **use of SML for OS** due to the following noteworthy features

- **Wide-area signal coverage** – broadcast satellites provide geographical coverage on continental scale (footprint).
- **Ease of reception** – within the satellite footprint, signals are strong and can be easily received with small sized parabolas (Ø ≤ 80 cm).
- **Ease of installation** – low-size (and cheap) parabolas can be easily put in place and aimed.
- **Low cost equipment** – commercial-grade equipment for satellite TV reception can be used. **DVB-S2 in Ku band (10-13 GHz).**
- **Ease of access to signal measurements** – measurements of RSL are made by sat. TV receivers with no authorization or fee.
- **High scalability of spatial-resolution** – if necessary, satellite terminals can be quickly and easily deployed to improve spatial density.
- **High temporal resolution** – RSL readings can be taken at 1 sample/minute or even more.
- **No installation and no maintenance of transmitters** – opportunity transmitters are serviced by their owners.
- **Green functioning** – no additional electromagnetic radiation is diffused into the environment for sensing.



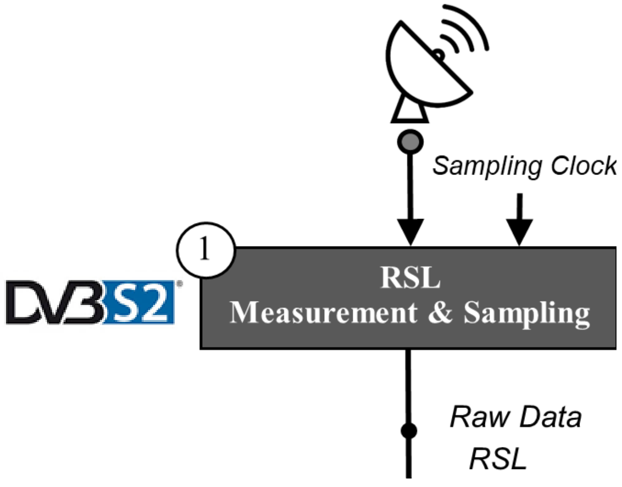


Ku footprint of Eutelsat 10A satellite, at 10°E

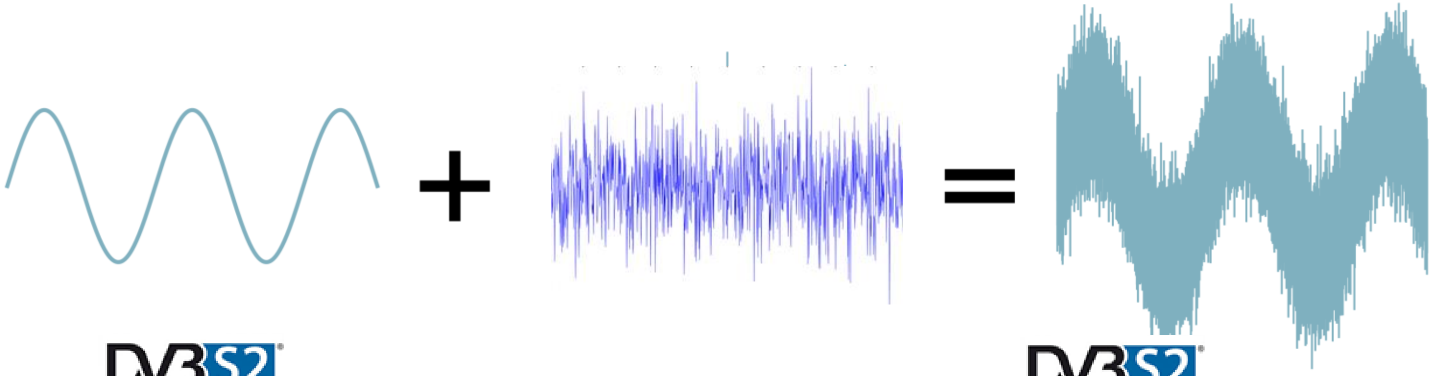


Many cities and regions worldwide exhibit a **pervasive diffusion** of terminals for direct reception of satellite TV broadcasts.
But, is this a real **enabler** for the development of an **ubiquitous** OS network?

RSL Definition, Measurement and Sampling



$RSL(k)$



signal → P_S [W]

noise → P_N [W]

signal + noise → $P_{RX}\ [\mathrm{W}] = P_S\ [\mathrm{W}] + P_N\ [\mathrm{W}]$

Commonly-used RF signal metric for the Received Signal Level (RSL)

1 Signal-to-Noise Ratio

$$RSL = \frac{P_S\ [\mathrm{W}]}{P_N\ [\mathrm{W}]} = \frac{E_s\ [\mathrm{J}]}{N_0\ [\mathrm{W \cdot s}]} \qquad RSL\ [\mathrm{dB}] = \frac{E_s}{N_0}\ [\mathrm{dB}] = 10 \times \log_{10} \frac{E_s}{N_0}$$

2 Received Power

$$RSL = P_{RX}\ [\mathrm{W}]$$

Commercial off-the-shelf decoder for DTH satellite broadcasting

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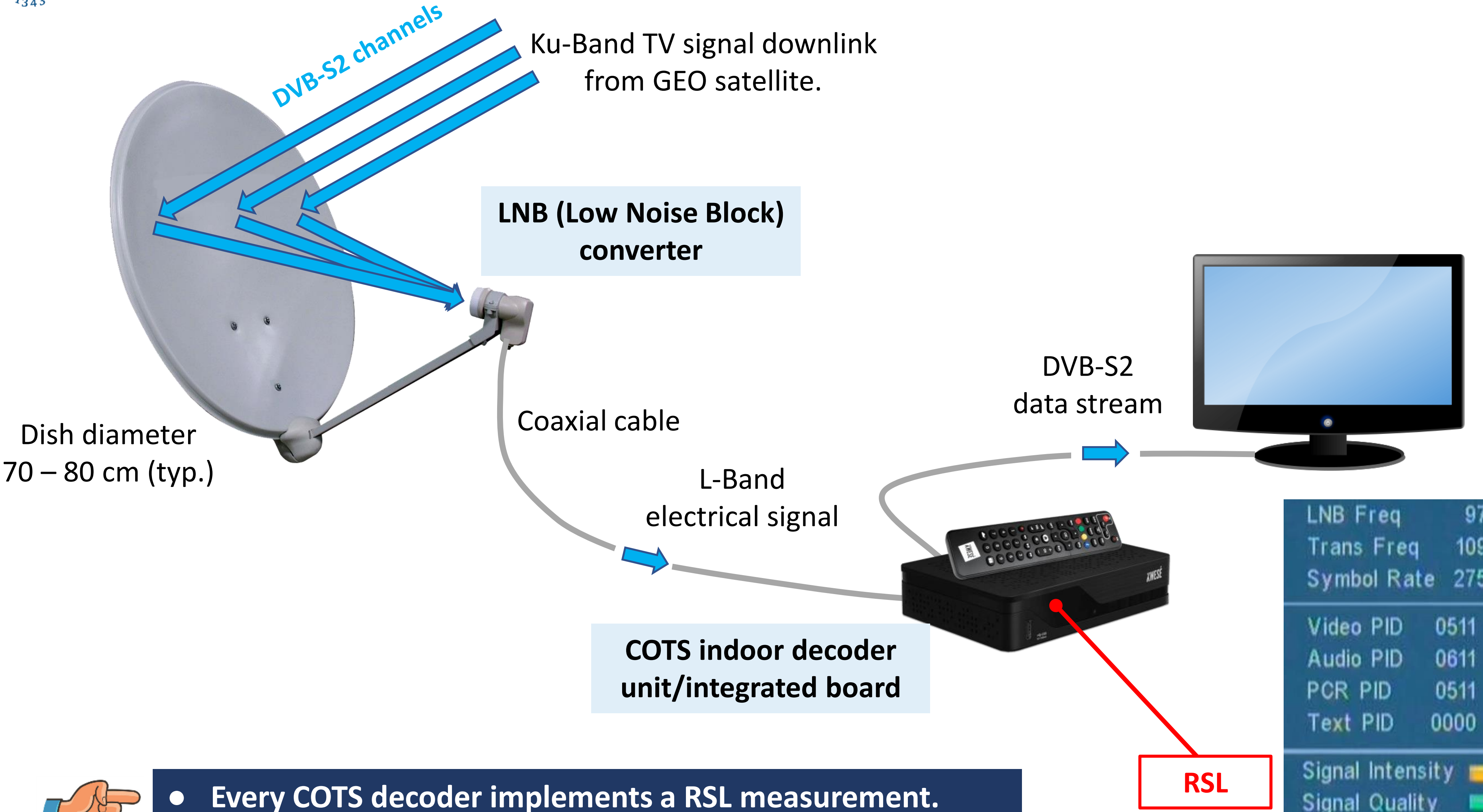
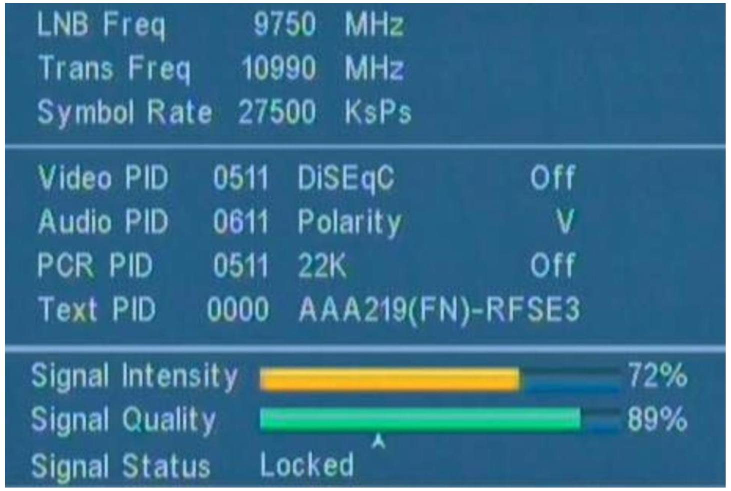
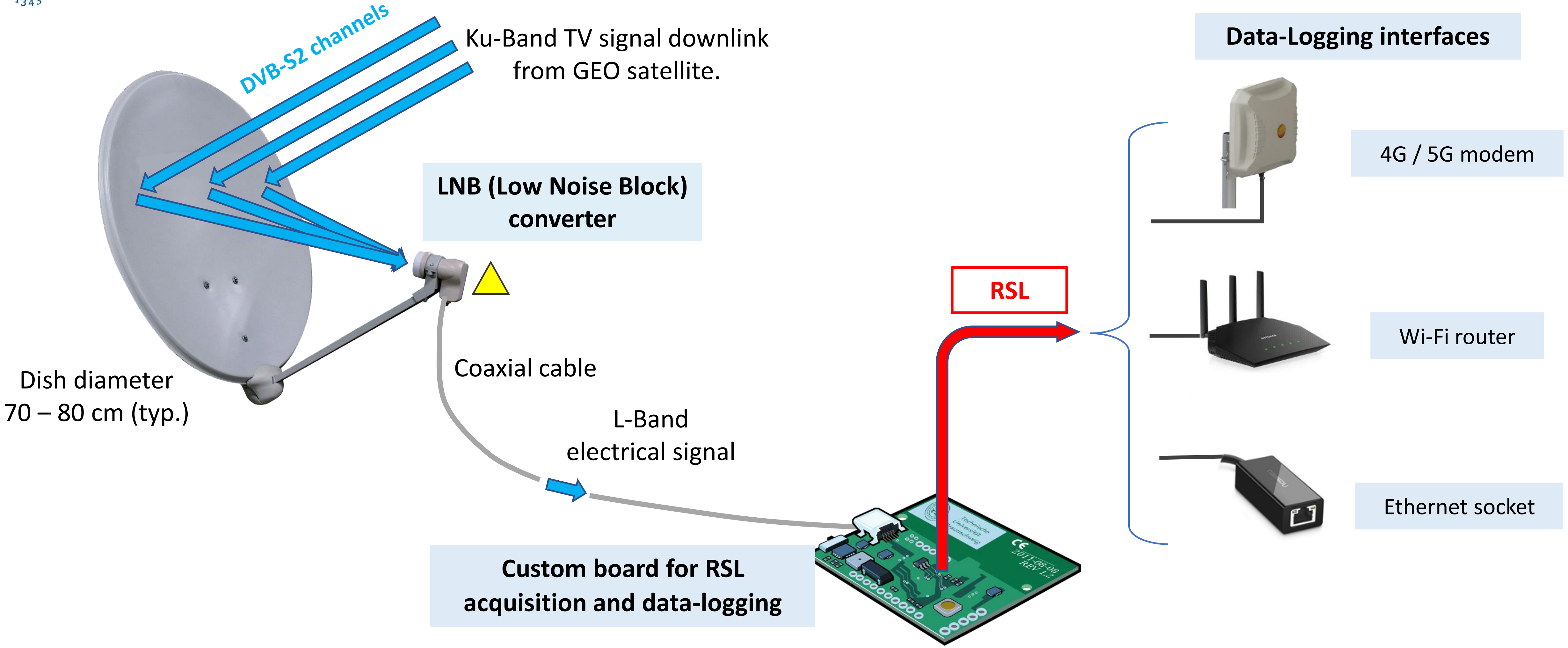




- **Every COTS decoder implements a RSL measurement.**
- **However, data logging functionalities are not available.**

Satellite TV receivers technology:
Custom board for RSL acquisition



- **Entails electronic design and manufacturing of a dedicated device for RSL acquisition.**
- **Requires the availability of a telecommunication infrastructure.**
- **Commercial-grade components may exhibit poor performance**

A few **hundreds of euro**

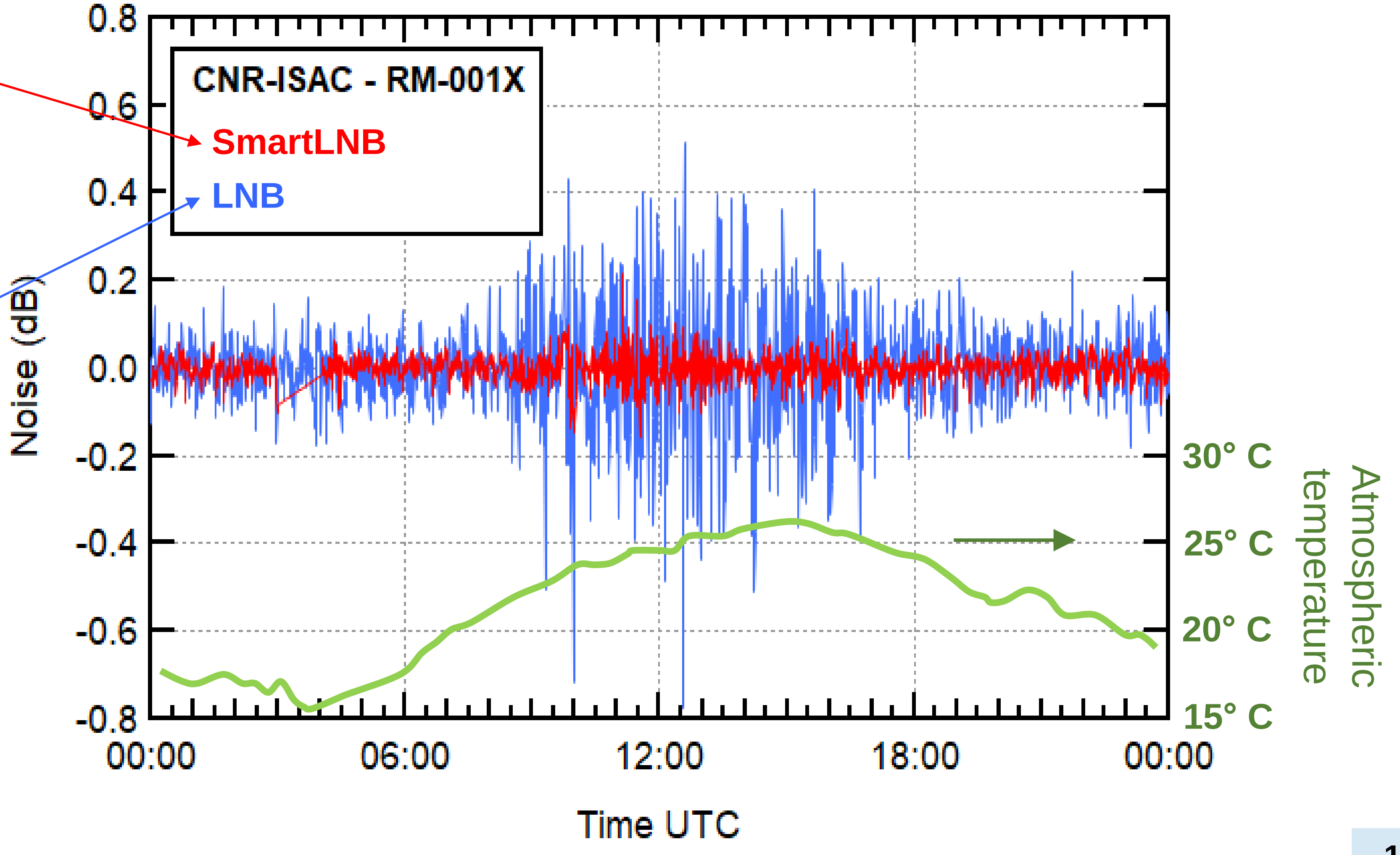
- High-end commercial device

Around **5 euro**

- Cheap and noisy electronics
- Poor quality plastic case
- Poor thermal shielding
- Dubious waterproofness
- Possible "wet antenna effect"

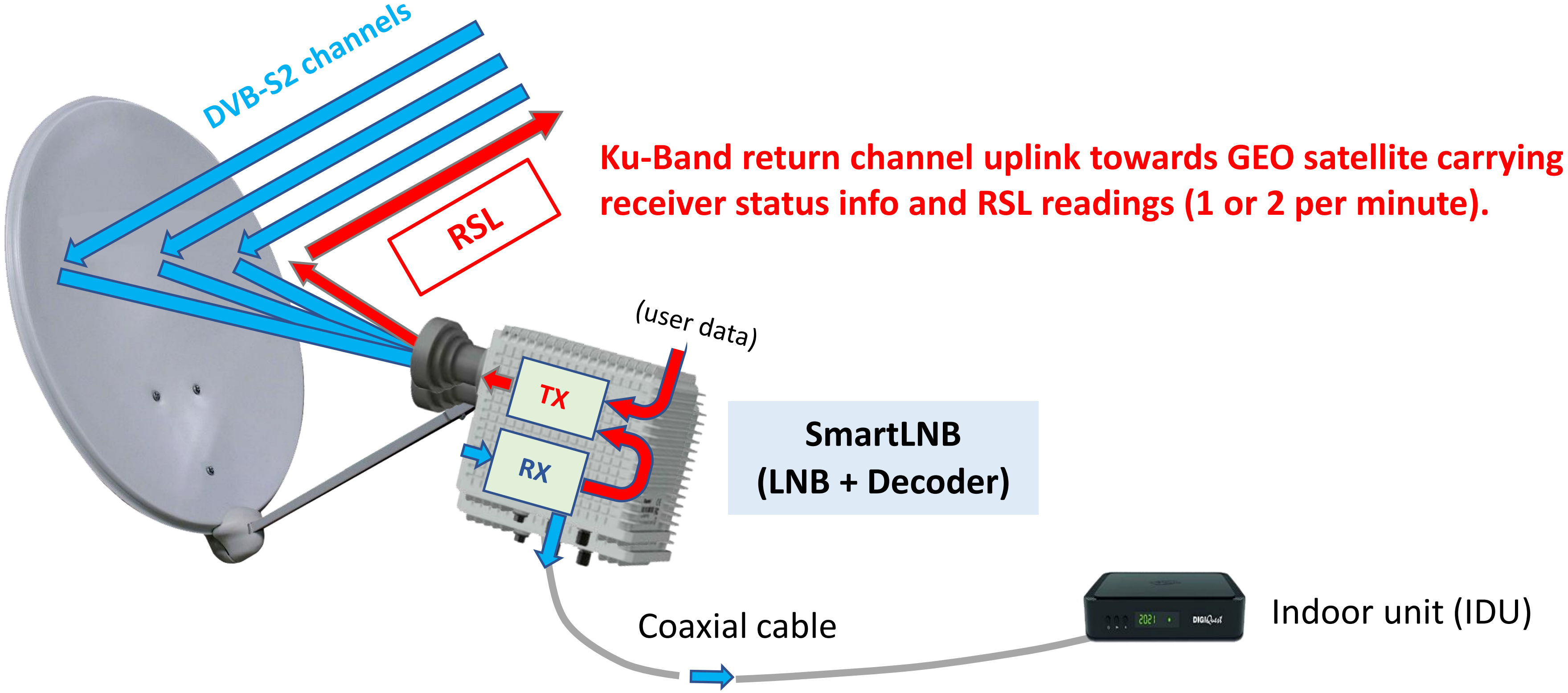
GEO satellite Eutelsat 10A, on 11.345 GHz (Ku-Band)

Rome, 29/05/2022 – Temperature: min 15° C – max 26° C – Clear sky



Satellite TV receivers technology:
The SmartLNB as a data acquisition and logging decvice for rain OS

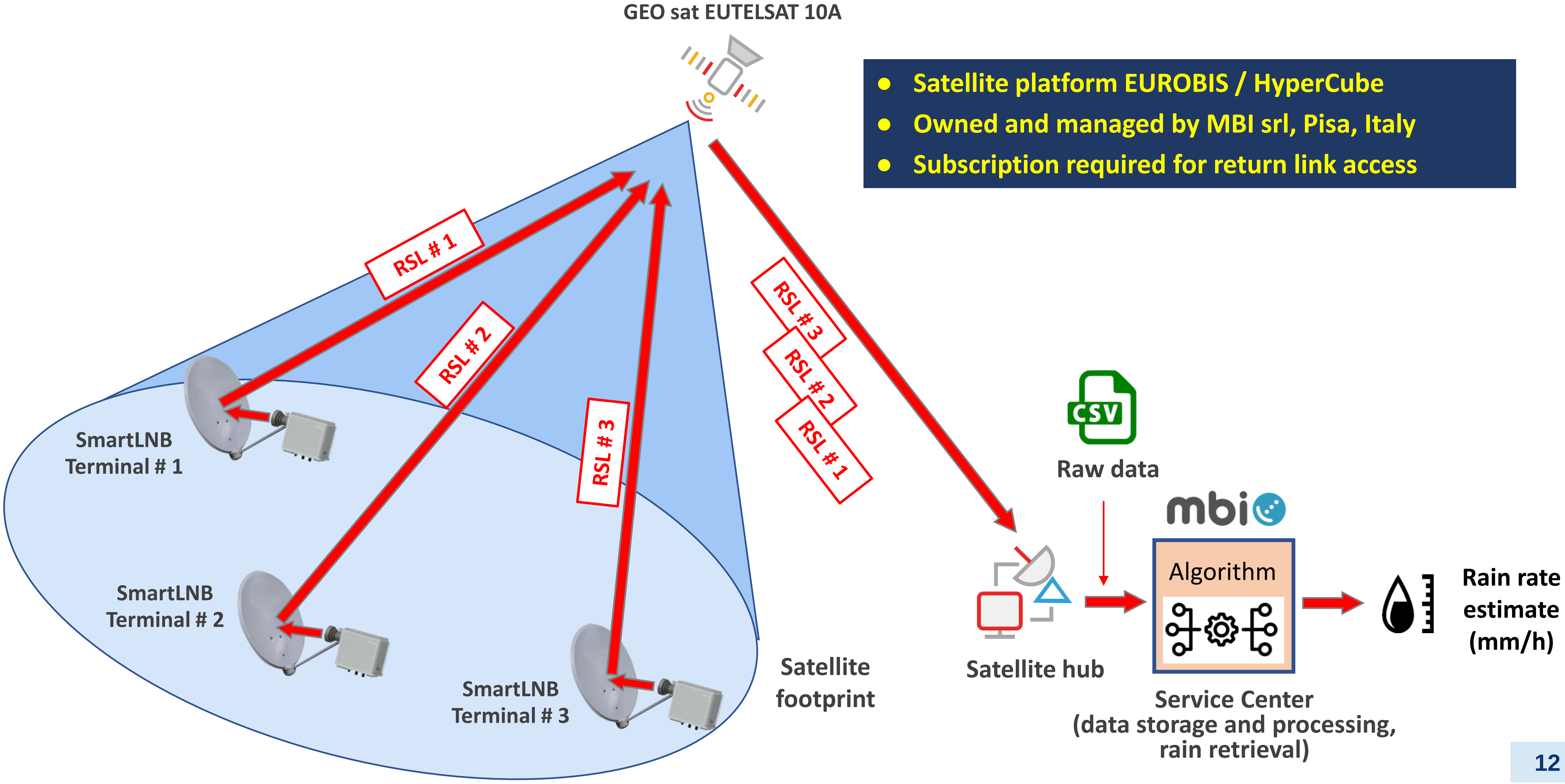
OpenSense score



- **SmartLNB innovative satellite terminal**
  - **Commercial** device
  - **Integrated**: LNB + decoder unit are combined into the same case
  - **Interactive**: two-way device
    - ***sensing:*** receives DVB-S2 channels and measures **RSL**
    - ***data-logging:*** transmits receiver status (incl. **RSL**) and user's data (interactive TV, IoT sensors)
- **Very appealing solution for the practical implementation of opportunistic satellite-based rain-sensing**

RSL harvesting from SmartLNB sensors via satellite return link

- Satellite platform EUROBIS / HyperCube
- Owned and managed by MBI srl, Pisa, Italy
- Subscription required for return link access



The "bad-looking" raw data from the SmartLNB

1 sample every 30 sec
(or 60 sec)

RSL

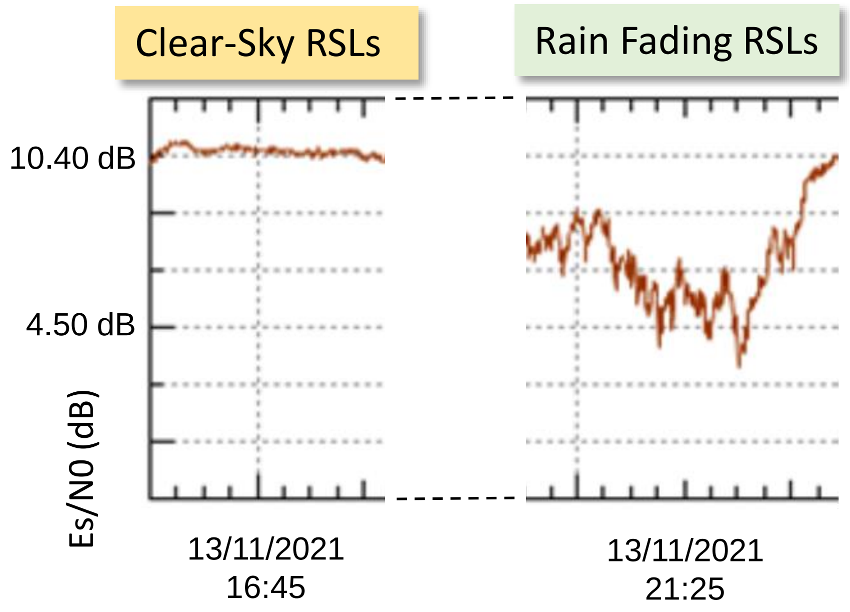
Timestamp	Es/N0 (dB)
13/11/2021 16:43:03	10.40667
13/11/2021 16:43:33	10.39000
13/11/2021 16:44:03	10.37667
13/11/2021 16:45:33	10.41000
13/11/2021 16:46:03	10.36667
13/11/2021 16:46:34	10.38667
//	//
13/11/2021 21:22:34	5.30000
13/11/2021 21:23:04	4.61379
13/11/2021 21:23:34	4.78000
13/11/2021 21:24:04	4.45769
13/11/2021 21:25:33	2.37143
13/11/2021 21:26:03	2.58929

Clear-Sky RSL

Rain Fading RSL

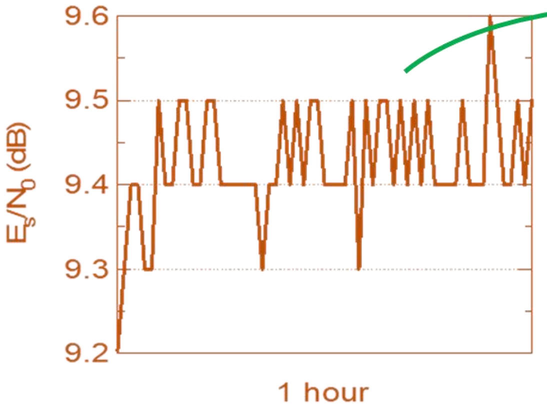
Rain Attenuation

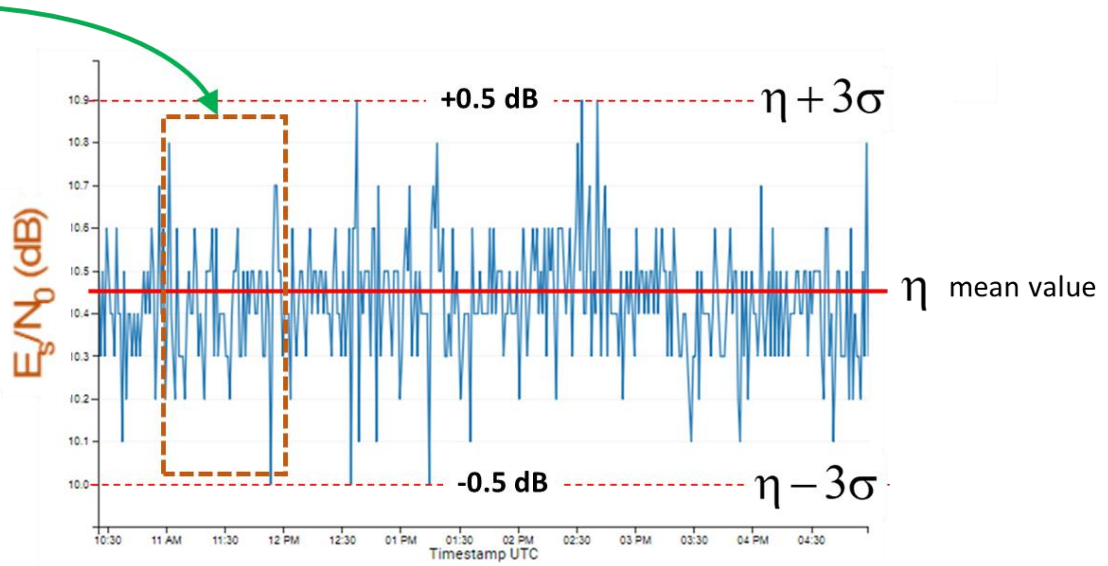
A [dB]



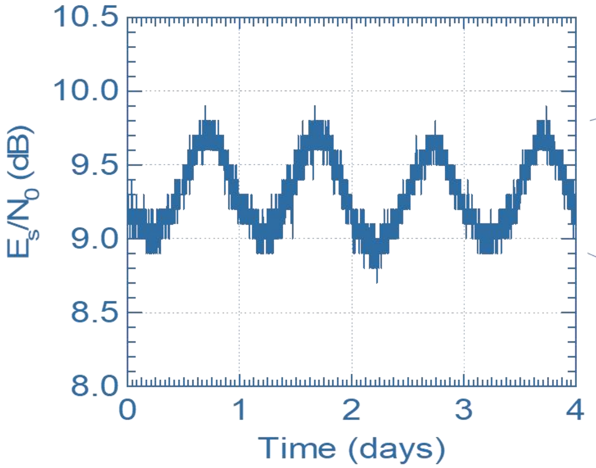
Noise and signal amplitude fluctuations

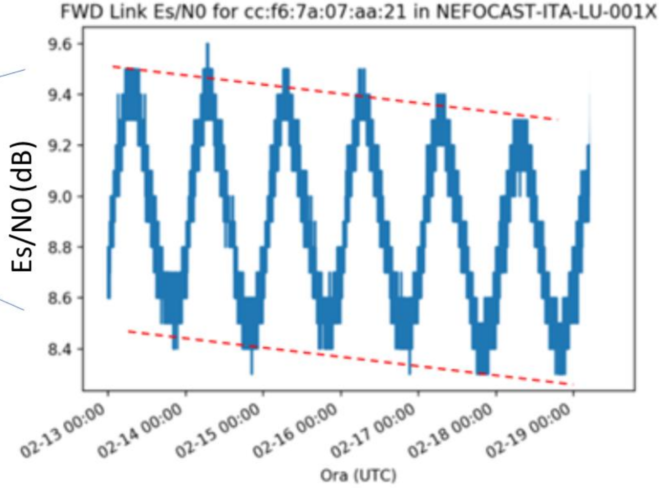
- Tropospheric scintillation noise and other noise contributions





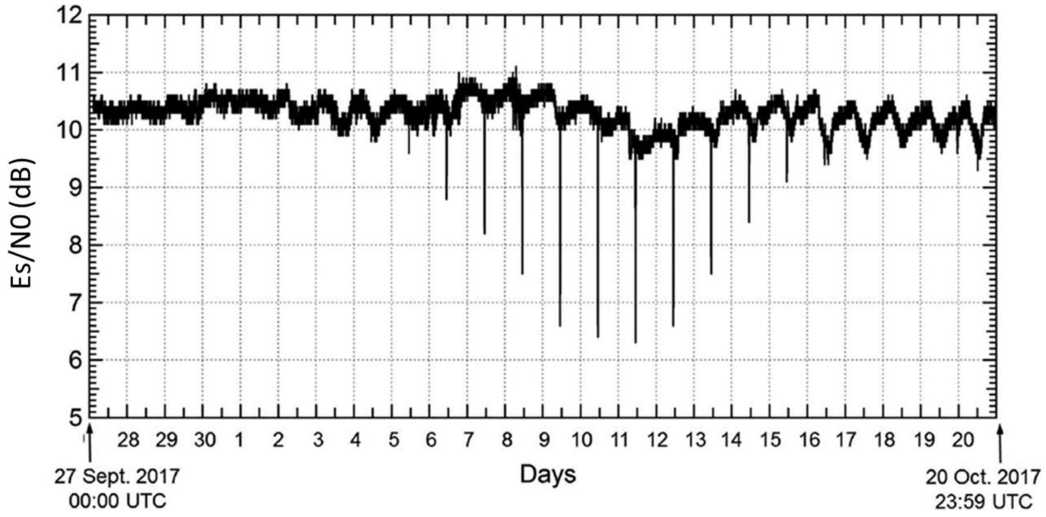
- GEO satellite orbit perturbations (inclination, drift)





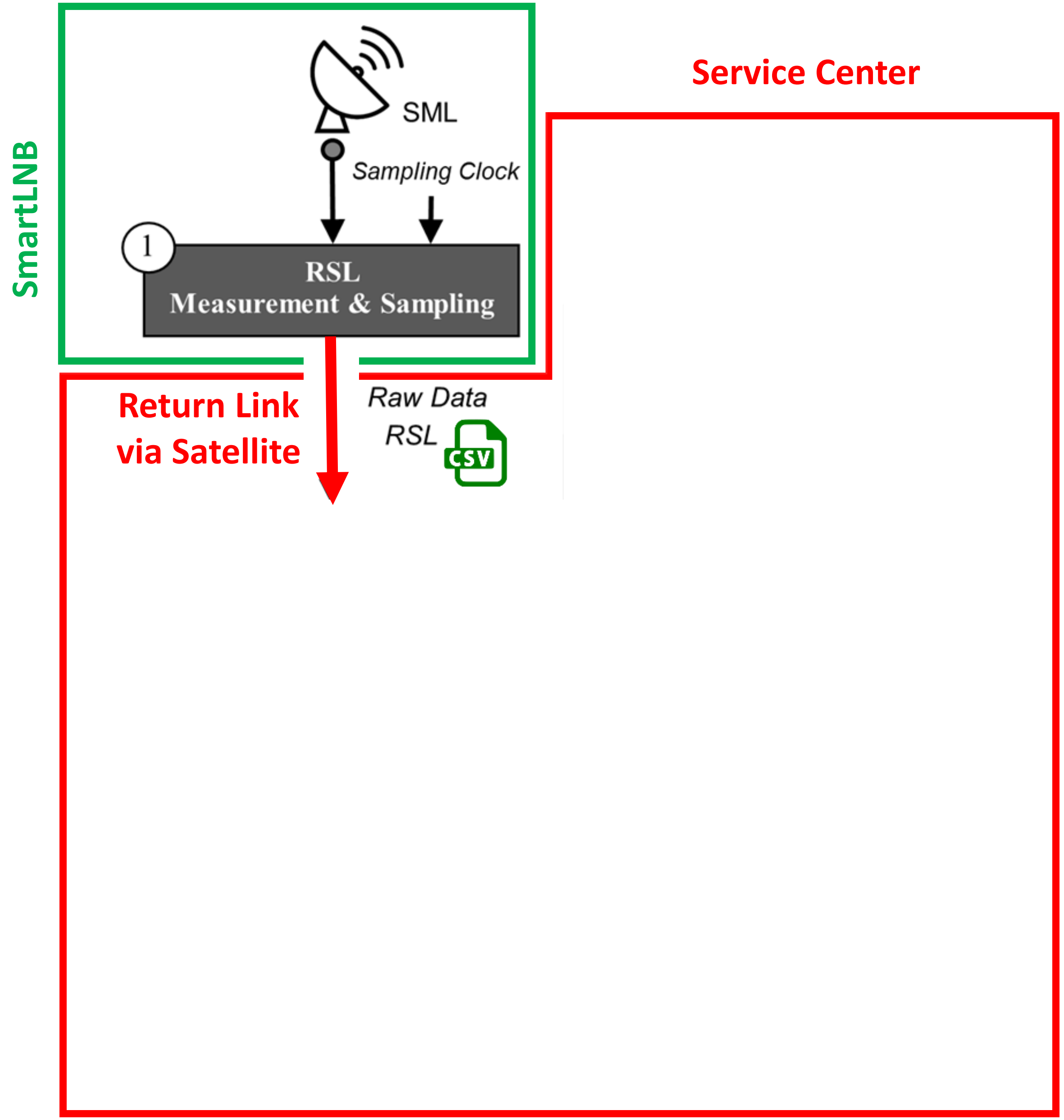
Noise and signal amplitude fluctuations

- Sun transit noise

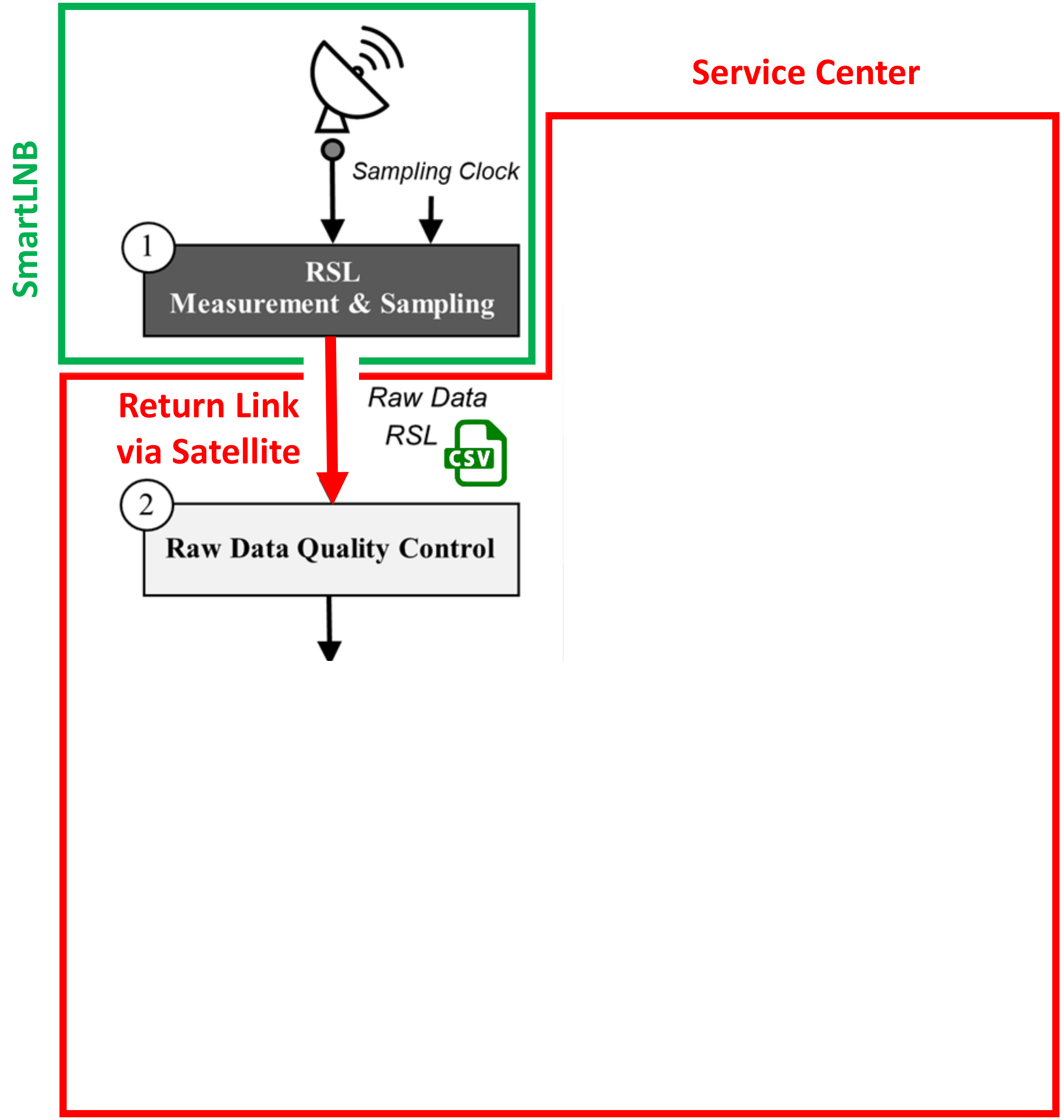


- Satellite operator's maneuvers / uplink fading

Flowchart of the basic processing steps for rainfall retrieval from OS data collected by a SML



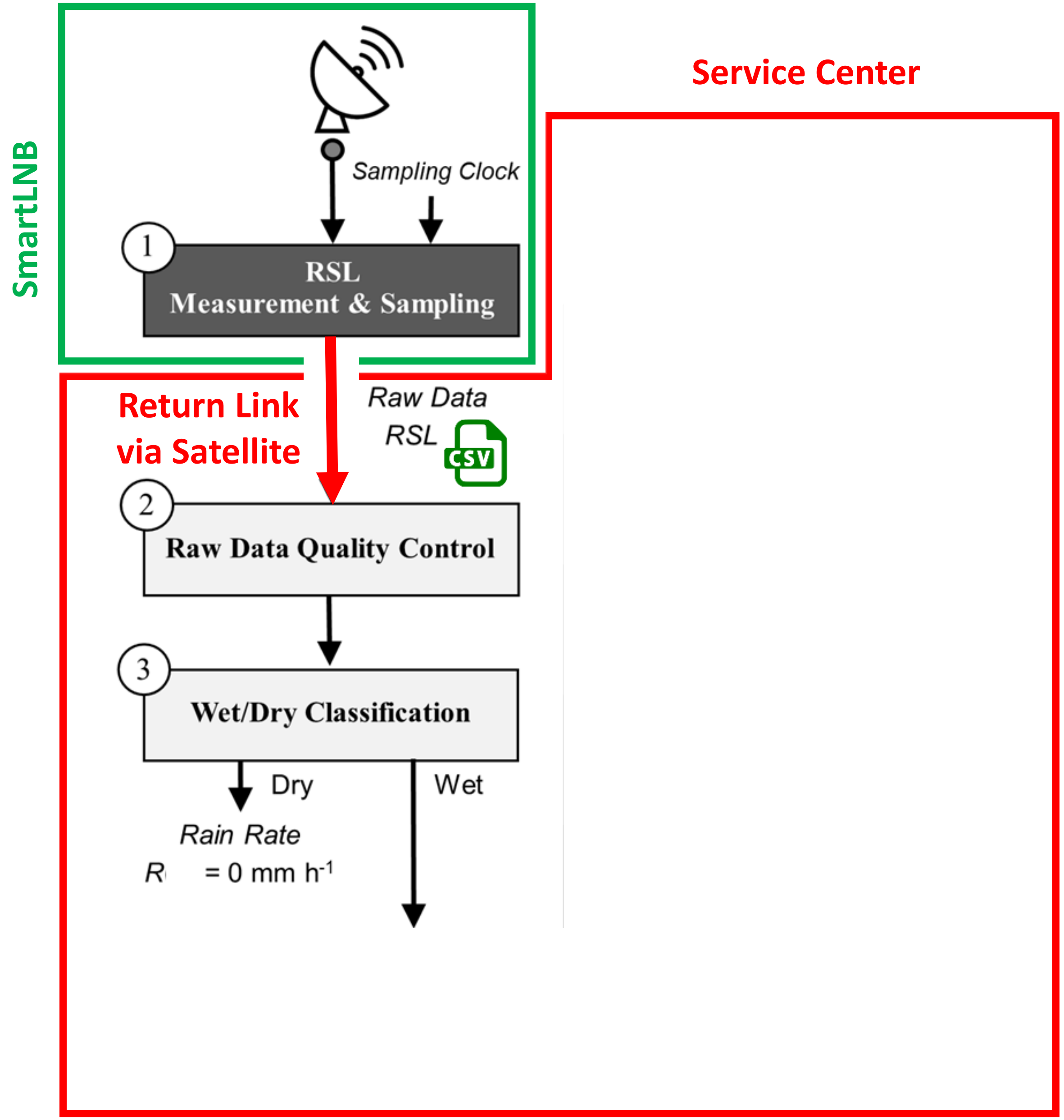
Flowchart of the basic processing steps for rainfall retrieval from OS data collected by a SML



(2) Raw Data Quality Control

- Telecom MW link and equipment not designed/optimized for sensing.
- SML receivers are commercial-grade products.
- **Standard tests on raw data**:
  - search for **missing data**, i.e., gaps in the time series;
  - identification of **outliers**, e.g. glitches or step-like variations in signal power;
  - identification of **receiver blinding due to sun transit**;
  - **cross-check** of data collected by different frequency channels of the same link or by nearby links.

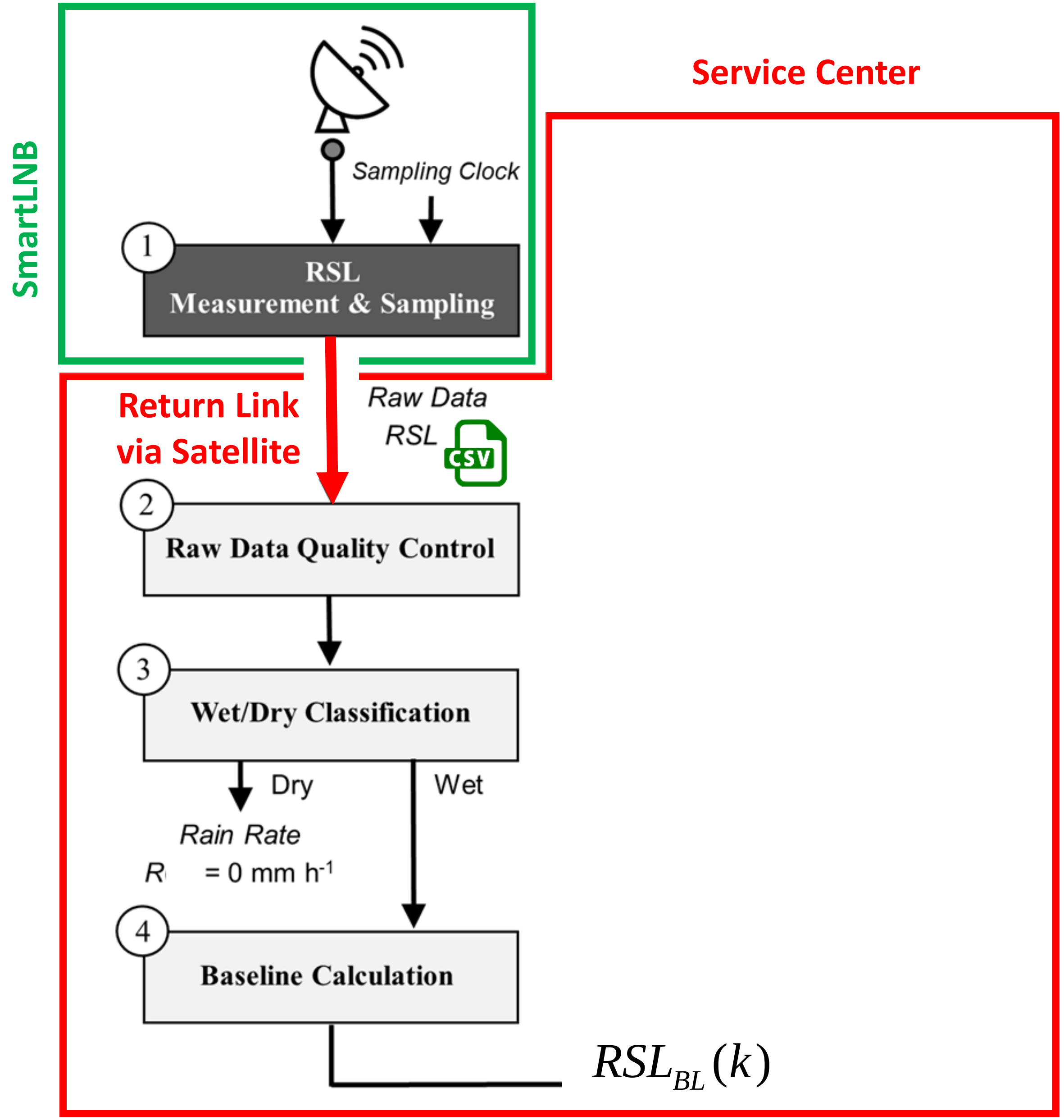
Flowchart of the basic processing steps for rainfall retrieval from OS data collected by a SML



(3) Wet/Dry Classification

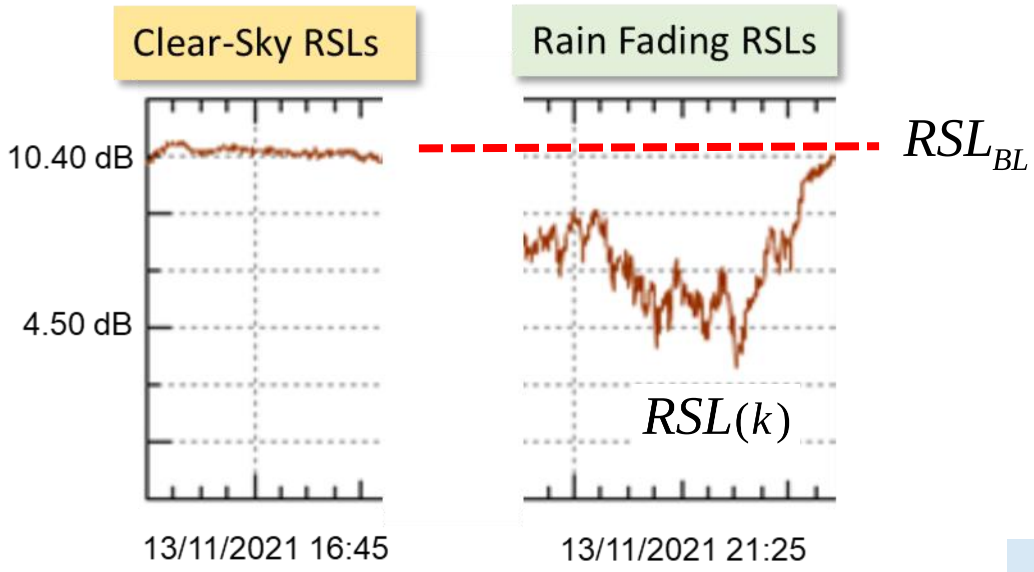
- Labeling the RSL samples as **wet** or **dry** :
  - enables detection of precipitation and measurement of duration;
  - eases subsequent rain intensity estimation.
- **Operation:**
  - detects rain event by exploiting the **different features** of RSL **wet** samples w.r.t. **dry** ones;
  - removes **scintillation noise**;
  - tracks RSL fluctuations due to **perturbations of GEO**.
- **Techniques:**
  - Kalman filtering;
  - AI methods for wet/dry classification of SML data
    - Artificial Neural Network
    - Support Vector Machine
    - Random Forest / Extremely Randomized Trees
    - Logistic Regression / Decision Tree

Flowchart of the basic processing steps for rainfall retrieval from OS data collected by a SML

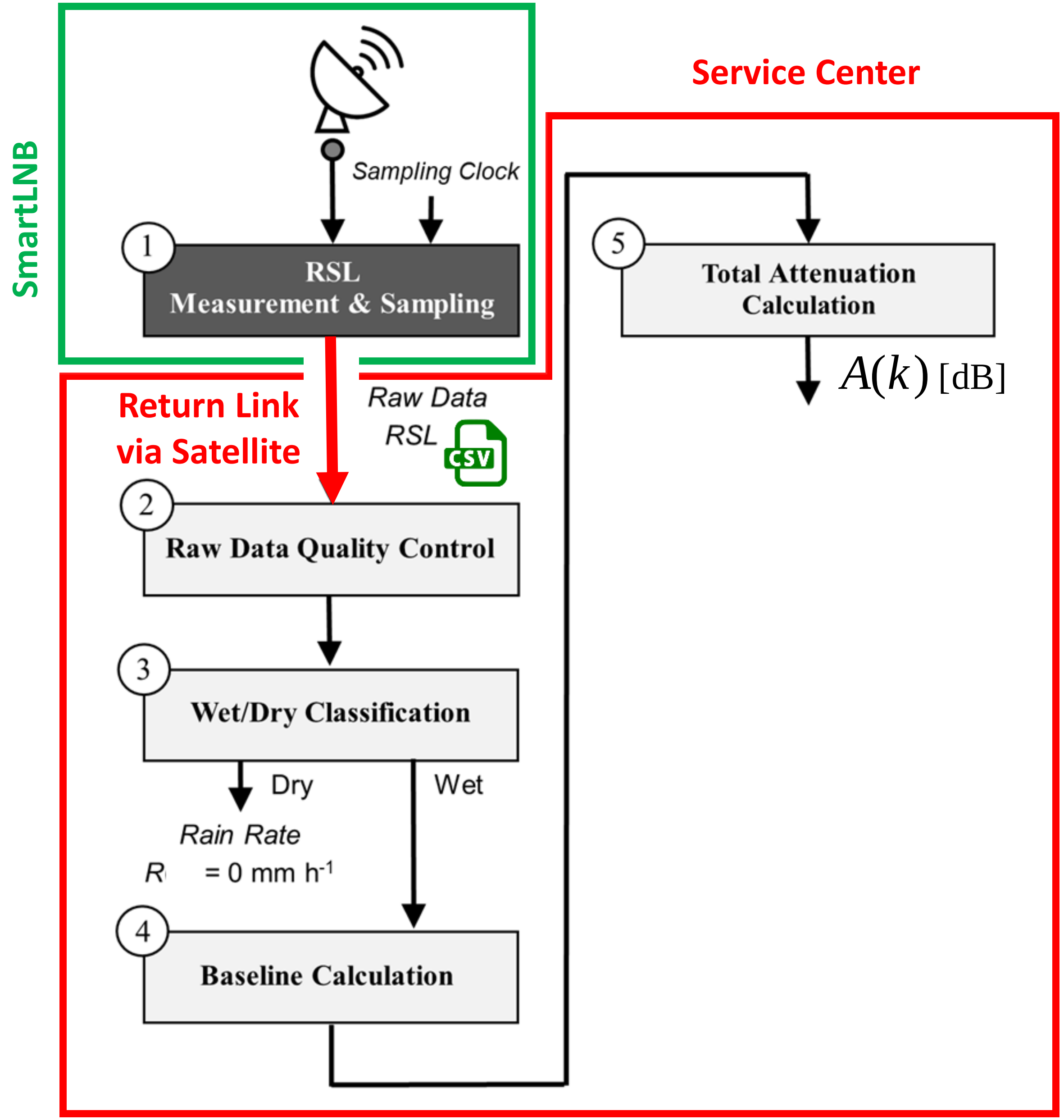


(4) Baseline Calculation

- RSL **baseline** value for dry conditions is necessary for rain attenuation estimation.
- Techniques:
  - It is assumed constant during the entire rain event, as:
    - the last "dry" RSL reading;
    - the median RSL value over the preceding 24 dry hours.
  - It is updated at every sample by dynamic techniques (sliding windows, filters, etc.).



Flowchart of the basic processing steps for rainfall retrieval from OS data collected by a SML



(5) Total Attenuation Calculation

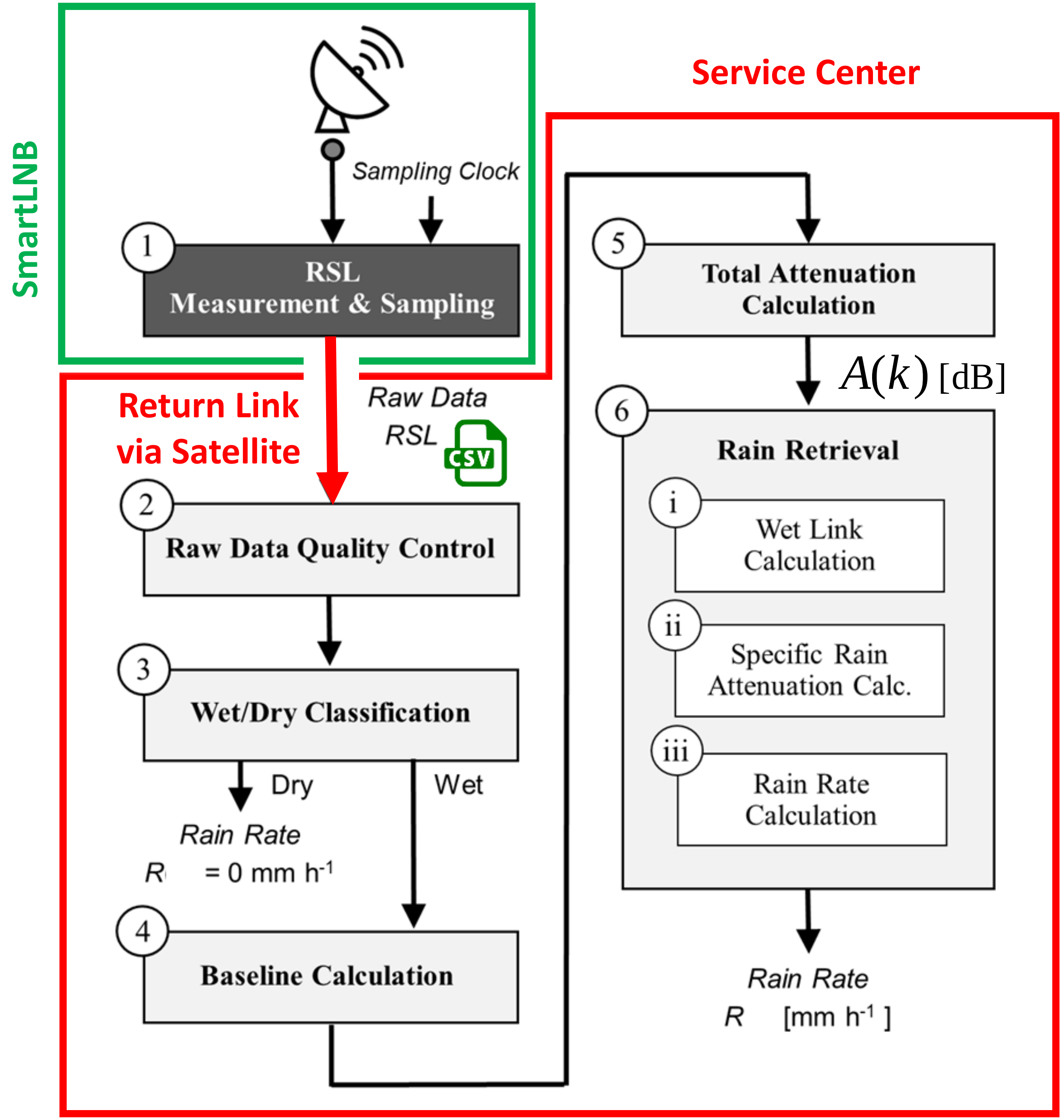
- *RSL* is a **power level**

$$A(k)\,[\text{dB}] = \overbrace{P_{BL}(k)\,[\text{dBm}]}^{RSL_{BL}(k)} - \overbrace{P_{RX}(k)\,[\text{dBm}]}^{RSL(k)}$$

- *RSL* is a **Signal-to-Noise Ratio**

$$A(k) = \frac{\overbrace{SNR_{BL}(k)}^{RSL_{BL}(k)}}{\underbrace{SNR(k)}_{RSL(k)}} \times \alpha + \beta$$

Flowchart of the basic processing steps for rainfall retrieval from OS data collected by a SML



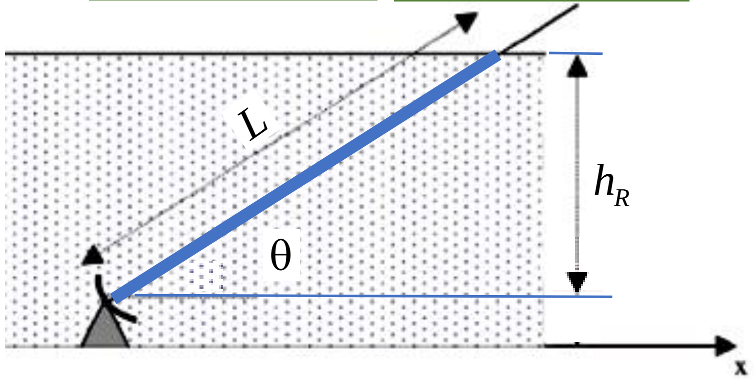
(6) Rain Retrieval

- **2-layer ITU model**

i. Wet Link Calculation

ITU-R Rec. P.618 ITU-R Rec. P.839

$$\frac{h_R}{\sin\theta} = \boldsymbol{L}\,[\text{km}]$$



ii. Specific Rain Attenuation Calculation

ITU-R Rec. P.618

In

$$\frac{\boldsymbol{A}\,[\text{dB}]}{\boldsymbol{L}\,[\text{km}]} = \boldsymbol{\gamma}\,[\text{dB/km}]$$

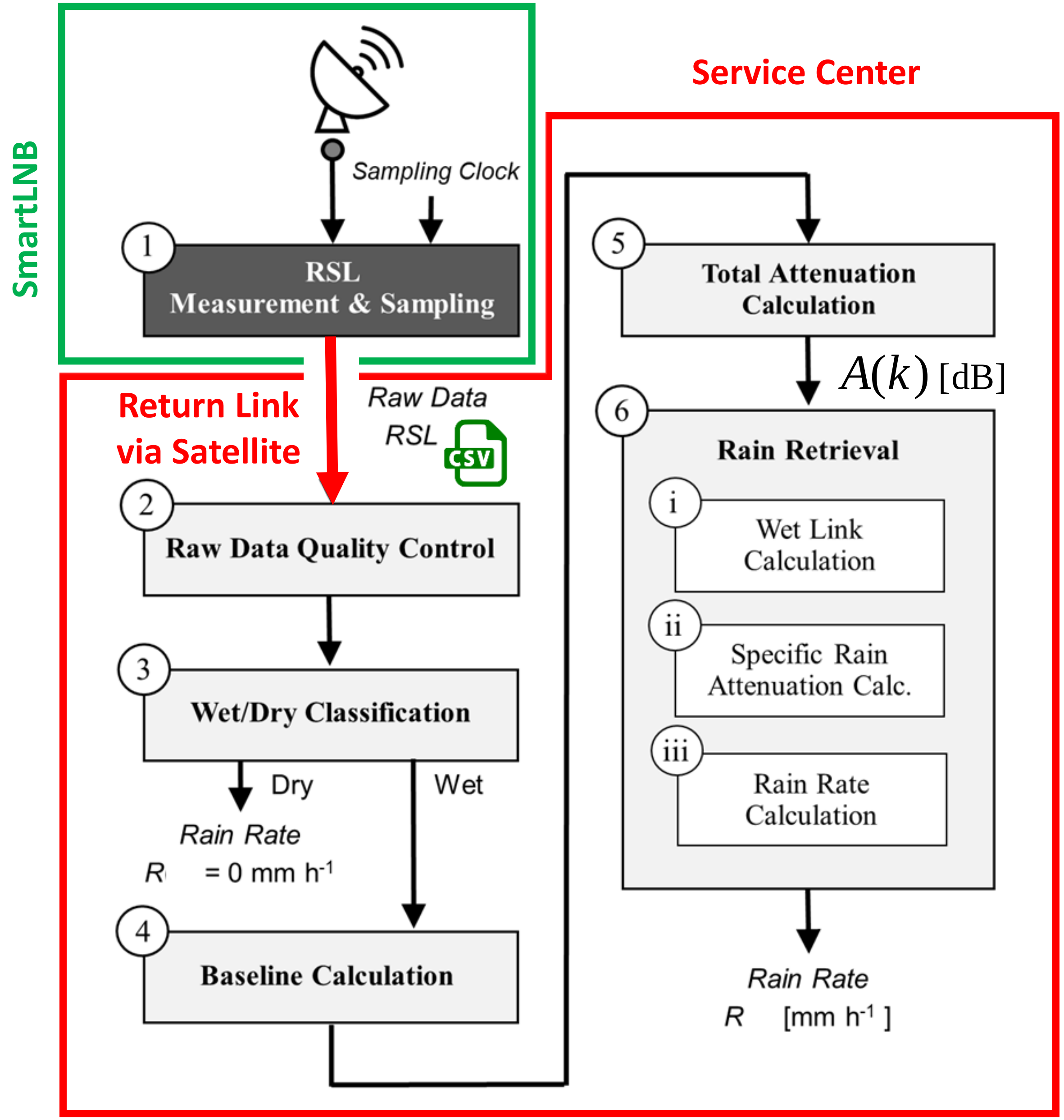
iii. Rain Rate Calculation

ITU-R Rec. P.618

$$\left(\frac{\gamma}{a}\right)^{\frac{1}{b}} = R$$

Out

Flowchart of the basic processing steps for rainfall retrieval from OS data collected by a SML



(6) Rain Retrieval

- **2-layer ITU model** (*overestimates* rain intensity)

In → **Out**

$$\boldsymbol{A}\,[\text{dB}] = \boldsymbol{\gamma}\,[\text{dB/km}] \times \boldsymbol{L}\,[\text{km}] = \boldsymbol{a} \times \boldsymbol{R}^{\boldsymbol{b}} \times \boldsymbol{L}$$

- **3-layer tropospheric model,** which takes into account also for the effects of the **melting layer (ML)**

In → **Out**

$$\boldsymbol{A}\,[\text{dB}] = F(\boldsymbol{R})$$

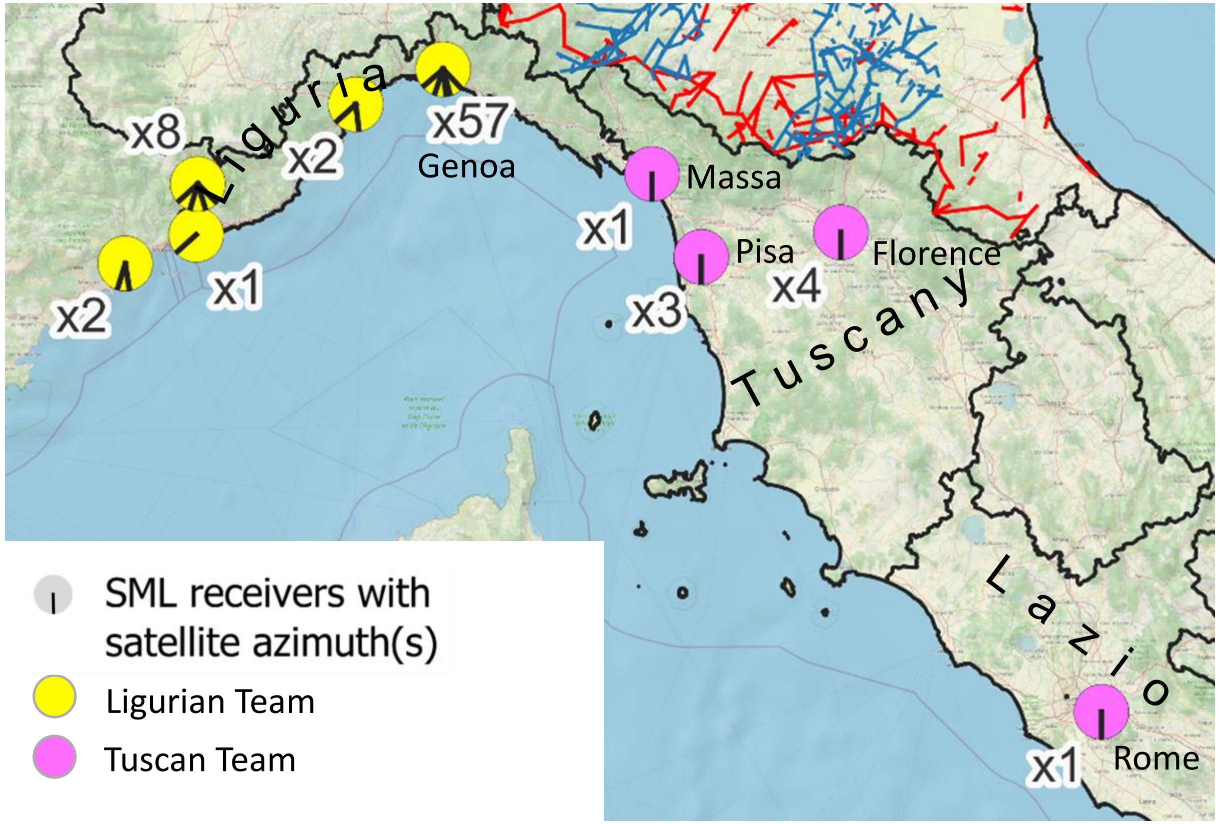
Ku-band propagation in
- Liquid-Layer
- Melting-Layer

International patent application No. PCT/IB2021/056594
International filing date 21 July 2021

SML-based OS activities in Italy

OpenSense score

Test ranges for SML-based OS of rain deployed in Italy



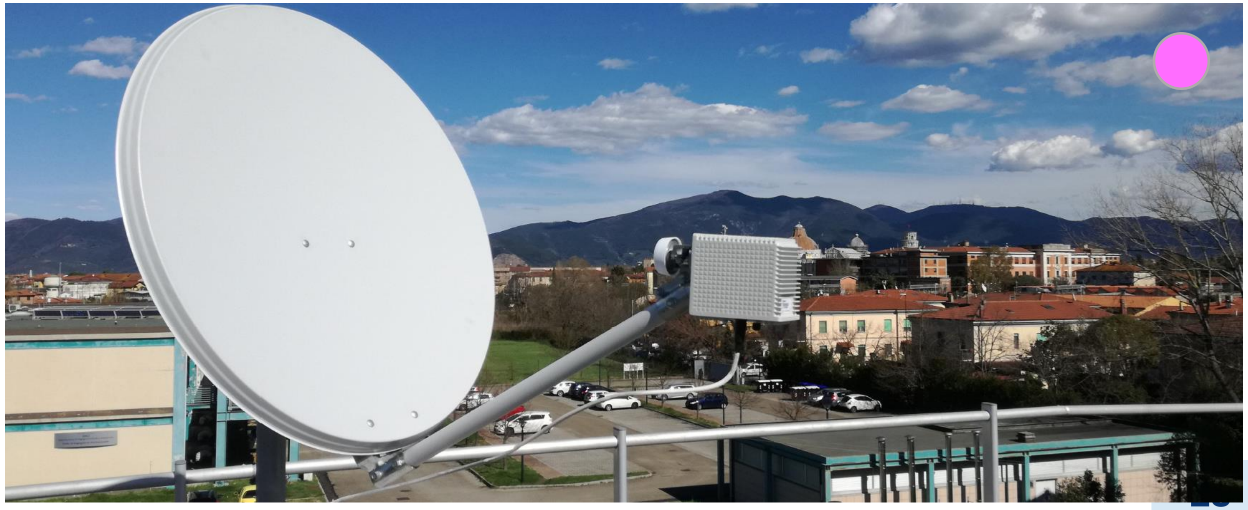
SML-based OS characteristics

- Sensitivity: **approx. 1 mm/h**
- Saturation: **80 mm/h @ h_0 = 4.5 km, 160 mm/h @ h_0 = 1 km**
- Detection range: **1.2 km @ h_0 = 1 km, 5.6 km @ h_0 = 4.5 km**
- Time resolution **30" – 60"**

Recent projects carried out in Italy on SML-based OS of rain

	Project (Duration) web site	Funds	Test-Range
Tuscan Team	SVI.I.C.T.PRECIP. (2016-19) www.nefocast.it	Tuscany Regional Govt	Tuscany, Lazio
Tuscan Team	INSIDERAIN (2021-22) www.insiderain.it	Tuscany Regional Govt	Tuscany, Lazio
Tuscan Team	SCORE (2021-25) score-eu-project.eu	E.C. H2020	Tuscany (Massa)
Ligurian Team	SIS.I.D.M.A. (2022-25) www.ponricerca.gov.it	PON 2014-20	Liguria (Genoa)

Opportunistic rain sensing terminal featuring a SmartLNB device, installed at the Department of Information Engineering, University of Pisa, Italy (43.7203° N, 10.3836° E), on a Ø 80 cm offset parabola, aimed at Eutelsat 10A satellite (10° E)



Wet/Dry Classification

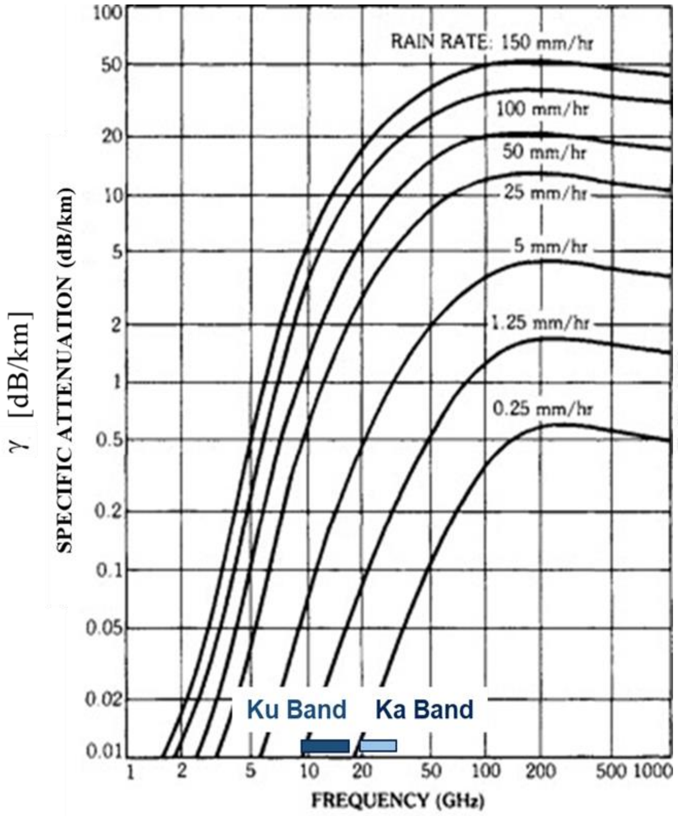
OS Number	Sampling Time	Integration Time	Observation Period	KPIs	Notes
26	1 min	5 min	22 rainy days	$Spe \approx .80$ $Rec > .80$ $HM \approx .80$	Ref.: WR data Wet threshold: ref. > 0.1 mm h^{-1} Method: AI
				$Spe < .50$ $Rec > .95$ $HM \approx .60$	Ref.: WR data Wet threshold: ref. > 0.1 mm h^{-1} Method: statistical
1	1 min	1 min	34 rain events in 12 months	$Rec = .65$ $FAR = .15$	Ref.: Disdrometer data Wet threshold: ref. > 0.1 mm h^{-1} Method: statistical

Rain Intensity Retrieval

OS Number	Sampling Time	Integration Time	Observation Window	KPIs	Notes
37	1 min	10 min	16 rainy days	$RMSE_r = 1.6$	Ref.: RG data Threshold: Ref. > 0.2 mm
6	1 min	Event duration	12 months	$NMAE = .55$ $RB = 19\%$	Ref.: RG data Threshold: Ref. > 1.5 mm
4	1 min	Event duration	12 months	$NMAE = .50$ $RB = -18\%$	Ref.: Disdrometer data Threshold: Ref. > 0.1 mm h^{-1}
3	1 min	Event duration	24 months	$NMAE = .11$ $PCC = .924$	Ref.: RG data Threshold: Ref. > 1 mm

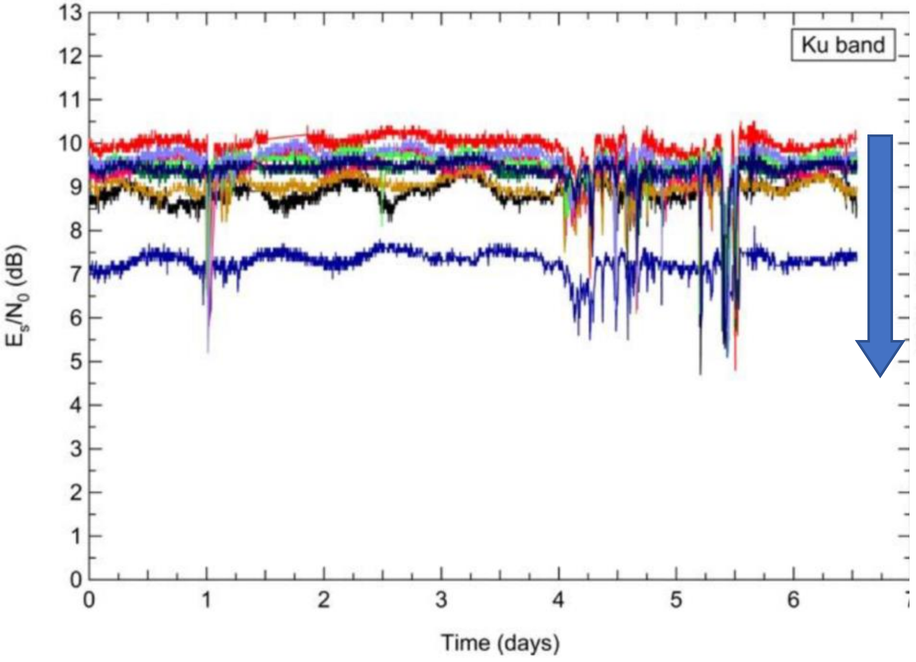
From: R. Nebuloni et al. *"A Review of Technical Challenges in Opportunistic Rainfall Estimation Using Satellite and Terrestrial Microwave Links,"* under review, 2025.

Future developments and trends: migration to higher frequency bands (Ka-Band and above)

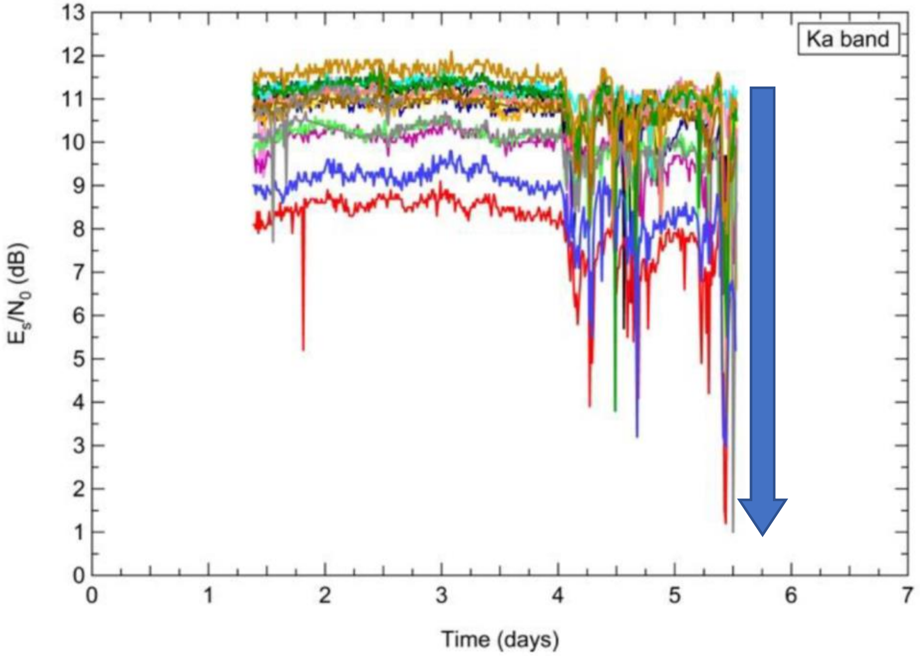


Raindrop size distribution: Laws and Parsons, 1943
Terminal velocity of raindrops: Gunn and Kinzer, 1949
Dielectric constant of water at 20°C: Ray, 1972

Rain fading dynamics @ **Ku**



Rain fading dynamics @ **Ka**

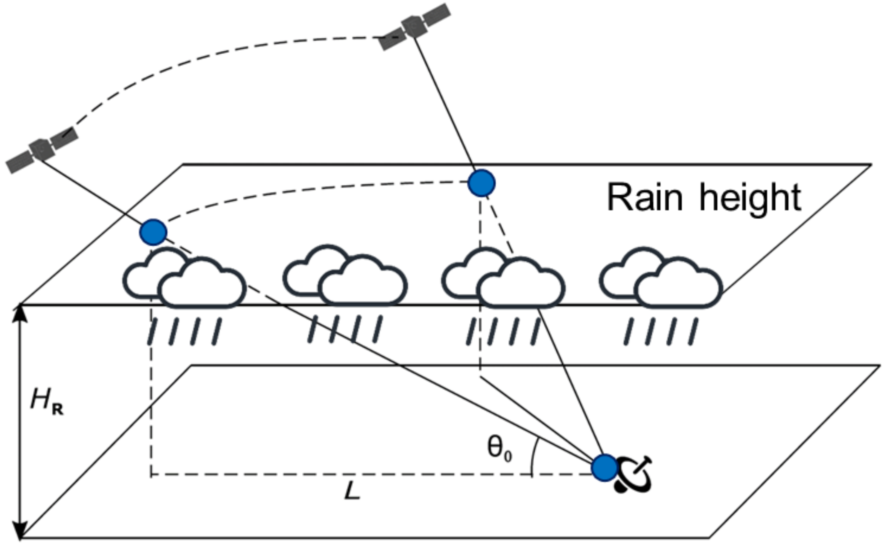


Improved sensitivity at low rain rates

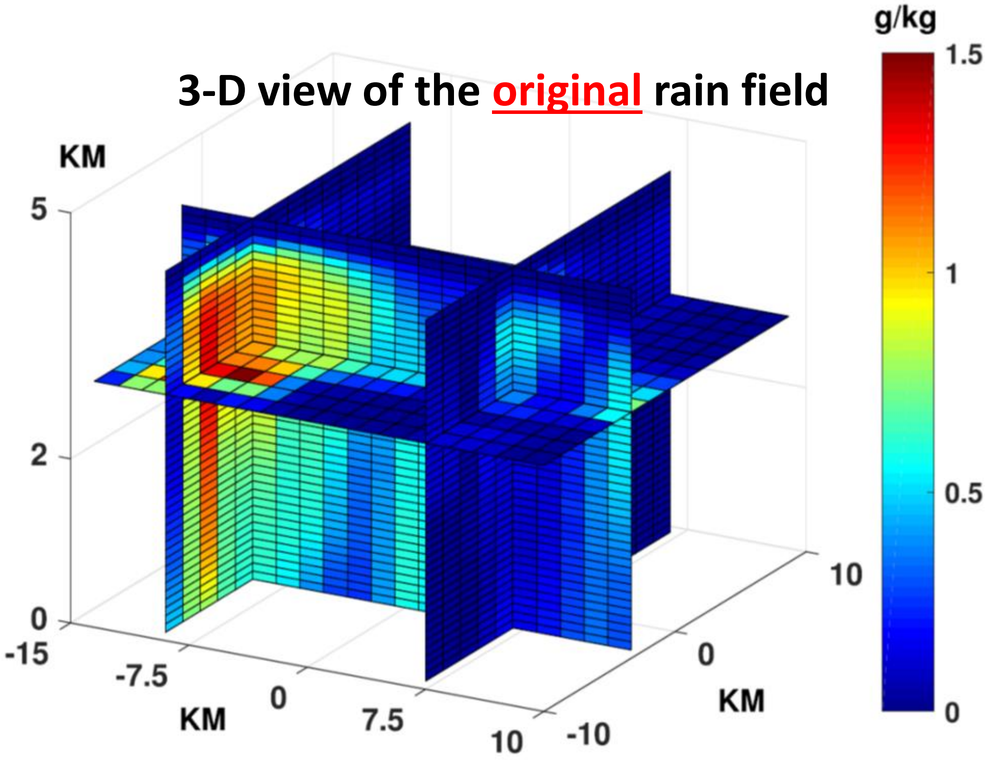
Future developments and trends:
LEO Mega-Constellations (Ku- and Ka-Bands)

- The **moving multiple links of a LEO** constellation pass through the Earth atmosphere **along many different directions**.
- LEO satellites linked to their ground terminals can be used to **scan the rainfall field in a vertical plane**.

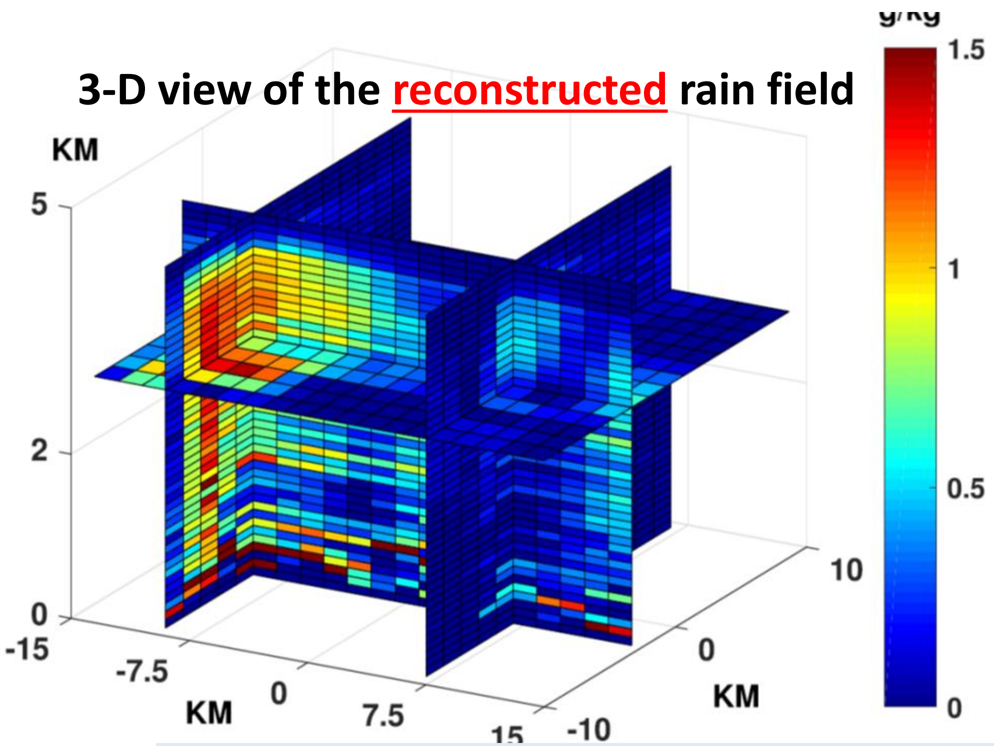
Xi Shen et alii, "3-D Tomographic Reconstruction of Rain Field Using Microwave Signals From LEO Satellites: Principle and Simulation Results", IEEE TGRS, Aug. 2019.



3-D view of the original rain field



3-D view of the reconstructed rain field



3D reconstruction of the precipitation

Future developments and trends: Artificial Intelligence

- R Y Mardyansyah et al. "Artificial Intelligent for Rainfall Estimation In Tropical Region: A Survey," *IOP Conf. Series: Earth Environ. Sci.*, 1105 012024, 2022. DOI 10.1088/1755-1315/1105/1/012024

Authors	Year	Dataset	ML Techniques	Validation	Issues
Diba et al. [15]	2021	Terrestrial and satellite link	ANN, LSTM	DSDm	More experiments are required on satellite link
Barthès & Mallet [17]	2013	Satellite link	MLP-ANN	RG, WR	Long duration rain events (> 3h) are required for model improvement
Xian et al. [18]	2020	Satellite link	SVM, LSTM, GA-BP	DSDm	Methods underestimate heavy and extreme rain due to lack of samples
Gharanjik, A. et al. [20]	2018	Satellite link	ANN	RG	Inaccurate labeling of path-averaged data due to in-situ rainfall measurement
Mishra et al. [21]	2018	Satellite link	LSTM	RG, WR	Several differences enhance the dissimilarities between link and radar estimates

WR = Weather Radar.
RG = Rain Gauge.
DSDm = Disdrometer.

- Gianoglio, et al. "Rain Discrimination with Machine Learning Classifiers for Opportunistic Rain Detection System Using Satellite Micro-Wave Links," Sensors 2023, 23, 1202. https://doi.org/10.3390/s23031202
- Scognamiglio, et al. "Deep Learning for Opportunistic Rain Estimation via Satellite Microwave Links," Sensors 2024, 24, 6944. https://doi.org/10.3390/s24216944

Use of AI/ML for wet/dry classification, rainfall intensity estimation, statistical feature extraction, precipitation maps retrieval etc.

Conclusions, comments and perspectives

- Practical example of **Integrated Sensing and Communication (ISAC):** a **symbiosis between sensing and communication** and a novel feature of next-generation networks (ITU, 6G).

- Terrestrial and satellite **MW communication infrastructures** are sources of **signals for oportunistic sensing (OS)**.

- Opportunistic estimation of rainfall intensity relies on the availability of **RSL measurements (Raw Data)**: difficult for terrestrial CMLs, much easier for SMLs.

- However:
  1) low cost commercial satellite receivers are unfit: **high quality receivers** are needed;
  2) satellite signals are affected by many impairments ("bad-looking" Raw Data): **clever processing** needed;
  3) propagation medium (troposphere), is complex and time varying in vertical: **accurate modeling** needed.

- Numerical results show accurate rain estimate from SMLs.

- Future evolutions:
  1) Higher frequency bands: **Ka, mmW**;
  2) Mega-constellations of **LEO satellites**;
  3) Use of **AI/ML** for wet/dry classification, rainfall intensity estimation, precipitation maps retrieval etc.

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- F. Giannetti, M. Moretti, R. Reggiannini and A. Vaccaro, "The NEFOCAST System for Detection and Estimation of Rainfall Fields by the Opportunistic Use of Broadcast Satellite Signals," in IEEE Aerospace and Electronic Systems Magazine, vol. 34, no. 6, pp. 16-27, 1 June 2019, doi: 10.1109/MAES.2019.2916292.

- Ortolani, A., F. Caparrini, S. Melani, L. Baldini, and F. Giannetti, 2021: An EnKF-Based Method to Produce Rainfall Maps from Simulated Satellite-to-Ground MW-Link Signal Attenuation. J. Hydrometeor., 22, 1333–1350, https://doi.org/10.1175/JHM-D-20-0128.1.

- E. Adirosi, L. Facheris, F. Giannetti, S. Scarfone, G. Bacci, A. Mazza, A. Ortolani, L. Baldini, "Evaluation of Rainfall Estimation Derived From Commercial Interactive DVB Receivers Using Disdrometer, Rain Gauge, and Weather Radar," in IEEE Transactions on Geoscience and Remote Sensing, vol. 59, no. 11, pp. 8978-8991, Nov. 2021, doi: 10.1109/TGRS.2020.3041448.

- S. Angeloni et al., "Enhanced Estimation of Rainfall From Opportunistic Microwave Satellite Signals," in IEEE Transactions on Geoscience and Remote Sensing, vol. 62, pp. 1-12, 2024, Art no. 4101312, doi: 10.1109/TGRS.2023.3349100.

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in European coastal cities

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opensenseaction.eu

Opportunistic precipitation sensing network

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	Meteo Pisa	www.meteopisa.it

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www.agr.unipi.it

www.acque.net

www.osservatorioadstatuas.it

lacapannaccia.com

International institutions that expressed their interest for these research activities

meteofrance.com

www.eutelsat.com

www.nasa.gov/goddard

SML-based OS rain sensor characteristics

OpenSense score

Settings for experimental measurements

Geographical area:	**North Western Tuscany / Lazio (Italy)**
Test sites:	**Pisa (10.4°E, 43.7°N), Massa (10.1°E, 44.0°N) / Rome (41.8°E , 12.6°N)**
Satellite:	**Eutelsat 10A @ 10°E**
Elevation:	**39° / 41.7°**
Frequency:	**11.345 GHz @ Ku band**
Downlink signal:	**DVB-S2**
RSL metric:	**E_s/N_0 (dB)**
RSL clear sky:	**approx. 10.5 dB**
RSL sensitivity:	**approx. - 2 dB**
RSL resolution:	**0.1 dB**
RSL sampling rate:	**1 – 2 sample/minute**

Performance Metrics Definitions

OpenSense score

Metric	Formula	Description
Specificity (Spe)	$\frac{TN}{n_{dry}}$	Indicates the classifier ability to predict dry observations. It ranges between 0 (worst score) and 1 (best score).
False Alarm Ratio (FAR)	$\frac{FP}{n_{c,wet}}$	It is the ratio of false alarms to predicted true samples. It ranges between 0 (best score) and 1 (worst score).
Recall (Rec)	$\frac{TP}{n_{wet}}$	Indicates the classifier ability to predict wet observations. It is also referred to as Sensitivity or Probability of Detection. It ranges between 0 (worst score) and 1 (best score).
Harmonic Mean (HM)	$\frac{2 \cdot Spe \cdot Rec}{Spe+Rec}$	It is the harmonic mean between Spe and Rec metrics. It ranges between 0 (worst score) and 1 (best score).

Metric	Formula	Description
Relative Bias (RB)	$\frac{1/N \sum_{i=1}^{N}(C_i - O_i)}{1/N \sum_{i=1}^{N}(O_i)}$	It is the average deviation between observed values (O_i), assumed as reference, and calculated (C_i) values, normalized to the mean of the observed values. N is the number of observations. It is often expressed in %. Values near 0 are good scores, negative values indicate underestimation and positive values indicate overestimation.
Normalized Mean Absolute Error (NMAE)	$\frac{1/N \sum_{i=1}^{N}\lvert C_i - O_i\rvert}{1/N \sum_{i=1}^{N} O_i}$	It is the mean absolute error divided by the mean of the observed values. It is often expressed in %. Lower NMAE values indicate better estimates.
Root Mean Square of relative Error (RMSE$_r$)	$\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{C_i - O_i}{O_i}\right)^2}$	Is the square root of the mean of the square of the relative errors $(C_i - O_i)/O_i$ between observed (O_i) and calculated (C_i) values. It is dominated by the largest values, due to the square operation.
Pearson Correlation Coefficient (PCC)	$\frac{\sum_{i=1}^{N}(O_i - \bar{O})(C_i - \bar{C})}{\sqrt{\sum_{i=1}^{N}(O_i - \bar{O})^2}\sqrt{\sum_{i=1}^{N}(C_i - \bar{C})^2}}$	It measures the linear relationship between observed (O_i) and calculated (C_i) values. $\bar{O}(\bar{C})$ represents the average of $O_i(C_i)$. It ranges from -1 to +1, where +1 indicates perfect linear correlation between the two datasets. However, a perfect linearity does not imply that the estimator is unbiased.