SAPIENZA
UNIVERSITÀ DI ROMA

FLORAD

FLOwer Constellation of Milliwave RADiometers for Tropospheric observation at Regional scale

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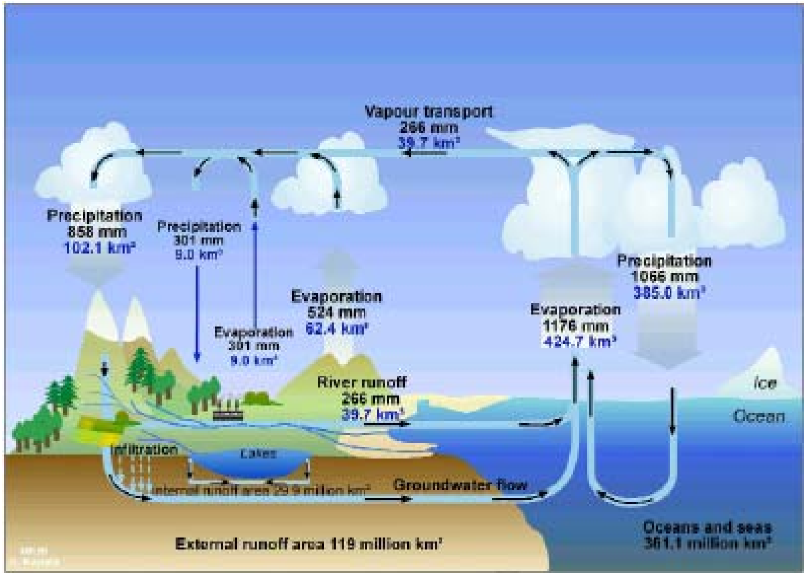
Avio propulsione aerospaziale
elital ELETTRONICA ITALIANA
nergal INGEGNERI DI IDEE

Outline of the presentation

- **Microwave radiometry of the troposhere**
  - Issues
  - FLORAD concept
- **Objective of FLORAD mission**
- **FLORAD scientific requirements**
- **FLORAD mission specifications**
  1. Milliwave Imaging Radiometer (FLOMIR)
  2. Micro-satellite preliminary features
  3. Flower Constellation preliminary design
  4. Ground segment preliminary design
- **Potential applications of FLORAD mission**
- **Numerical simulation of FLORAD observations**
- **Conclusions**

Satellite observation of troposphere

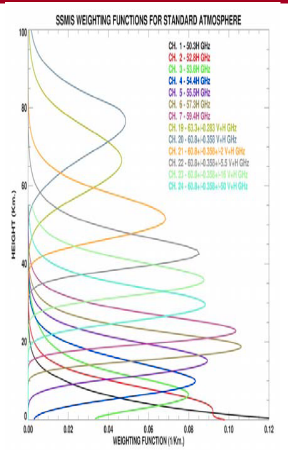
- **Millimeter-wave (MMW) passive observation of the tropospheric parameters is becoming an appealing goal within satellite radiometry applications.**
  - **Reduced size** of the overall system with respect to microwave (MW) sensor.
  - **Sounding** through window frequencies and various gaseous absorption bands at 50/60 GHz, 118 GHz and 183 GHz.
  - **Estimation** of tropospheric
    - temperature profiles
    - integrated water vapor
    - cloud liquid content
    - light rainfall and snowfall, using a differential spectral mode.

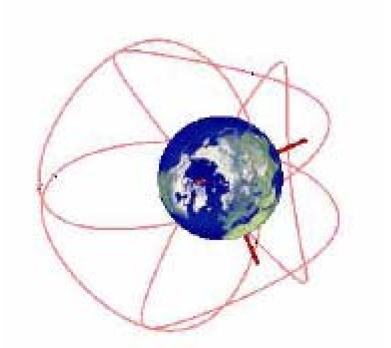


Objective of FLORAD satellite mission

Launch a constellation of micro-satellites with a MMW passive payload to retrieve tropospheric termo-dynamical profile and hydrological content

- **Application**
  - Tropospheric monitoring (e.g., over sea)
  - Assimilation within mesoscale models
  - Meteo-hydrological nowcasting
- **Technological**
  - MMW compact radiometers
  - Exploitation of micro-satellites
  - Flower constellation of satellites
- **Context**
  - Eumetsat priorities (MRD doc., 2007)
  - Multi-satellite synergy (e.g., GPM, A-Train)





FLORAD scientific requirements

- **EUMETSAT Post-EPS Mission Requirements Doc.**
  - Schlussel et al., 2007; Rizzi et al., 2006
  - 17 proposed missions for meteo-hydro-land applications
  - Final ranking:
    - Microwave Atmospheric Sounding: very high (2nd place)
    - Microwave Atmospheric Imaging; high (5th place)
- **Breakthrough requirements**
    - Global NWP, Regional NWP, Climate Prediction, Nowcasting

PARAMETER	Accuracy	Horizontal resol. (km)	Vertical resol. (km)	Temporal resol. (h)	Data Avail. Delay (h)
Cloud Liquid (NP, Prec.)	50 %	15	2	3	0.5
Cloud Ice (NP, Prec.)	50 %	15	2	3	0.5
Temperature	1.5 K	30	1	5	0.5
Water vapor	10 %	15	1	4	0.5

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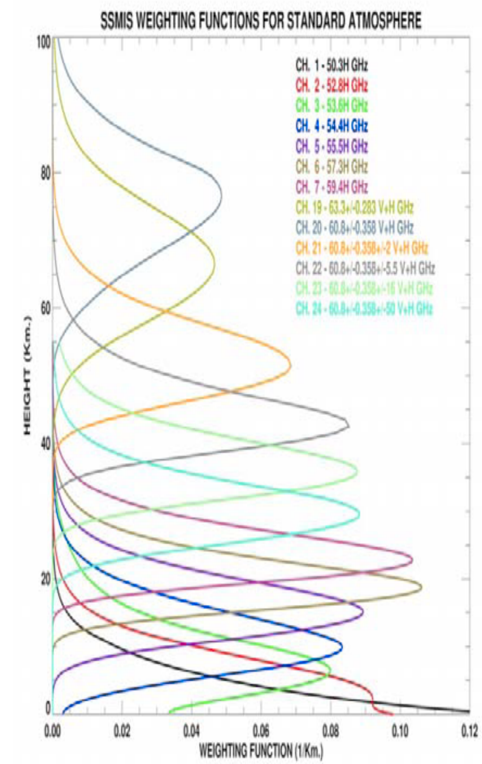
1. Milliwave Imaging Radiometer (FLOMIR)

- **Candidate channels**

Number	Centre frequency [GHz]	Heritage	Main application
1	6.925	AMSR-E, SMMR	SST, soil moisture
2	10.65	AMSR-E, TMI	SST, strong rain
3	18.7	AMSR-E	rain, sfc. wind, water vapour
4	23.8	AMSR-E, AMSU-A	rain, water vapour
5	31.4	AMSU-A	rain, cloud water, sfc. wind
6	50.30	AMSU-A, SSMIS	rain, cloud water, temp.
7	52.61	AMSU-A, SSMIS	rain, cloud water, temp.
8	53.24	AMSU-A, SSMIS	rain, cloud water, temp.
9	53.75	AMSU-A, SSMIS	rain, cloud water, temp.
10	89.0	AMSR-E, AMSU-A/B	rain, cloud water, snow
11	100.49 (118± 18.3)	new	rain, cloud water, snow, temp.
12	117.55 (118± 1.2)	new, could be combined	rain, cloud water, snow, temp.
13	120.16 (118± 1.4)	new, could be combined	rain, cloud water, snow, temp.
14	120.91 (118± 2.1)	new, could be combined	rain, cloud water, snow, temp.
15	186.67 (183.31±3.4)	AMSU-B, SSMIS, MHS	snow, water vapour
16	188.17 (183.31±4.9)	AMSU-B, SSMIS, MHS	snow, water vapour
17	189.42 (183.31±6.1)	AMSU-B, SSMIS, MHS	snow, water vapour
18	191.70 (183.31±8.4)	AMSU-B, SSMIS, MHS	snow, water vapour



- **Tradeoffs for compact systems**
  - Reduced sizes (antennas, feeder and circuits) and costs
  - Sounding and imaging capabilities

⇒ ***Avoid frequencies < 50 GHz***

⇒ ***Avoid frequencies > 130 GHz***

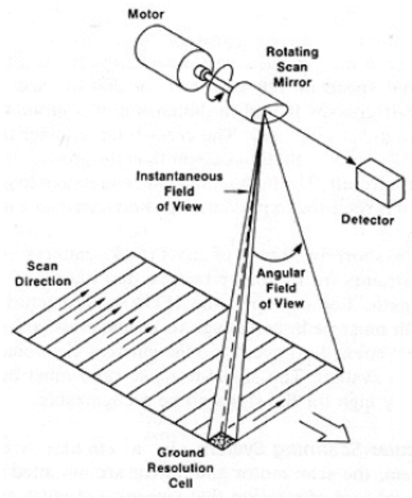
1. Frequency channels for FLOMIR

- **Preliminary selection of 16 channels**
  - 50-57 GHz band, 89 GHz band, 113-123 GHz band

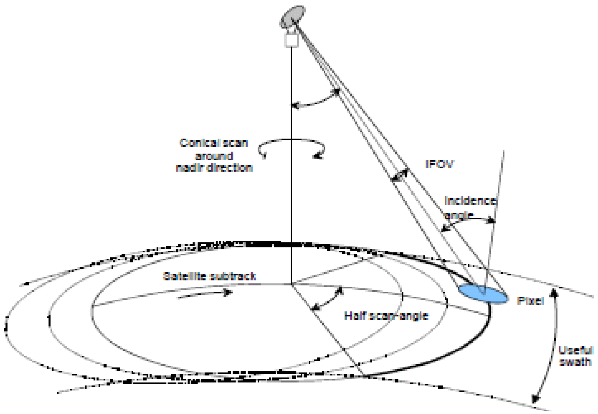
Central frequency (GHz)	Bandwidth (MHz)	Radiometric Precision (K)	Poalrization (H, V)	Comment
50.300	180	0.50	H, V	*Quasi-window channel– vapor, clouds*
52.800	400	0.30	H, V	*Quasi-absorbed channel – clouds and troposf. temperature*
53.596	170	0.40	V	*Quasi-absorbed channel – clouds and troposf. temperature*
54.400	400	0.40	V	*Absorbed channel – troposf. temperature*
54.940	400	0.30	V	*Absorbed channel – troposf. temperature*
55.500	330	0.40	V	*Absorbed channel – troposf. temperature*
57.2923	330	0.40	V	*Absorbed channel – stratosf. temperature*
57.2923 ± 0.217	80	0.60	V	*Absorbed channel – stratosf. temperature*
57.2923 ± 0.332±0.048	40	1.00	V	*Absorbed channel – stratosf. temperature*
57.2923 ± 0.332±0.010	10	1.20	V	*Absorbed channel – stratosf. temperature*
89.000	2000	0.30	H, V	*Window channel– vapor, clouds and rain*
118.75 ± 5.0	2000	0.50	H, V	*Quasi-absorbed channel – rain and temperature*
118.75 ± 3.0	1000	0.50	H, V	*Quasi-absorbed channel – clouds and temperature*
118.75 ± 2.1	800	0.70	H, V	*Absorbed channel – snow and temperature*
118.75 ± 0.7	400	0.75	H, V	*Absorbed channel – ice clouds and temperature*

1. FLOMIR scanning mode

- **Cross-track scanning**
  - ↑ Simpler implementation
  - ↑ Heritage for atmospheric sounding
  - ↑ Larger swath (implying a larger coverage
  - ↓ Variable Field-of-view (FOV) along scan
  - ↓ Variable incidence-angle along scan
  - ↓ Variable polarization along scan

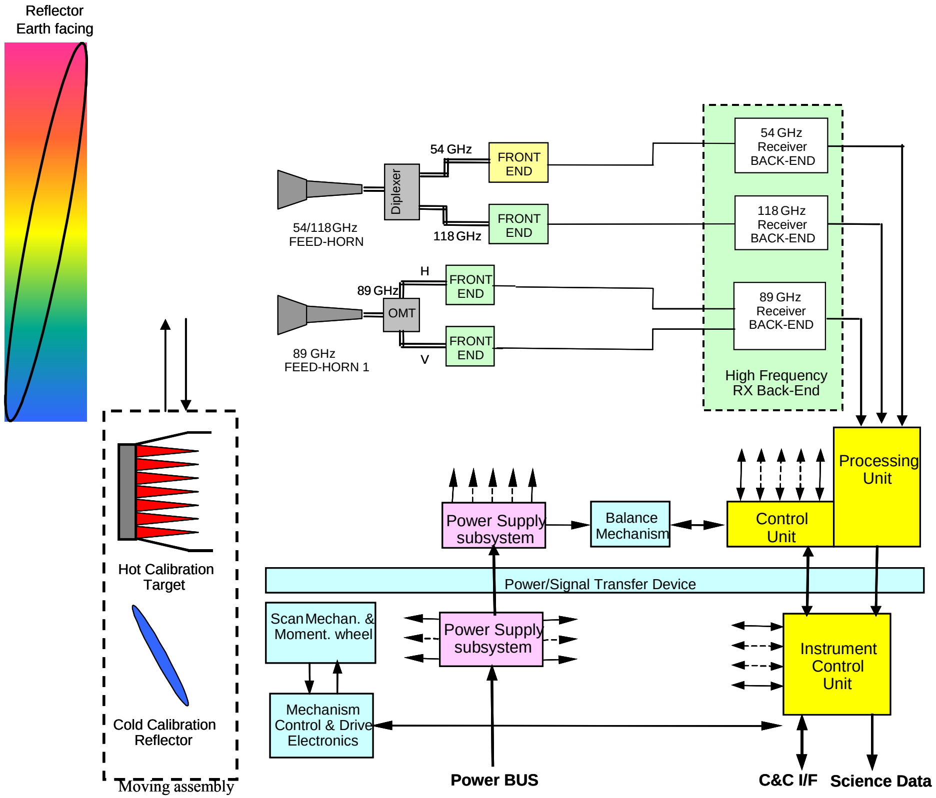


- **Conical scanning**
  - ↑ Constant (FOV) along scan
  - ↑ Constant incidence-angle along scar
  - ↑ Constant polarization along scan
  - ↓ More complicate implementation
  - ↓ Rarely used for sounding
  - ↓ Solar intrusions and effects



1. FLOMIR system configuration

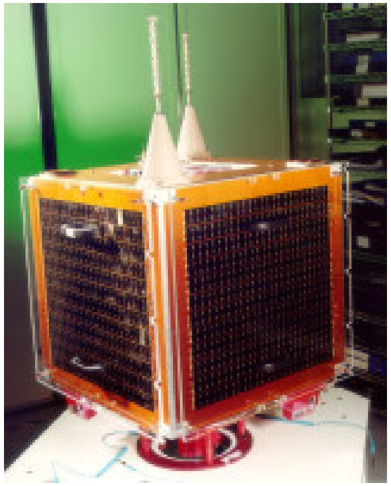
- **MMW Radiometer**
  - Total power module or Balanced Dicke module
    - Calibration issue, Milliwave Int. Circuits (MMIC) technology
  - Antennas: depending on the scanning mode (reflector/plane)
  - Wide-band corrugated horn clusters (SSB or DSB, OMT)



2. FLORAD micro-satellite

- **Micro-satellite platform preliminary design**
  - Weight: < 150 kg
  - Size: < 8 m^3
  - Power consumption: < 200 W
- **Subsystems**
  - Asset Control: magneto-torque, wheel
  - Asset Determination: magnetometer, GPS
  - Guidance Navigation System
  - Propulsion
  - Solar panels: 4 GaAs modules
  - Thermal control system
  - S-band Telemetry transponder
  - X-band data transmission
  - On-board processor and memory
  - Battery: Li-Ion
  - Payload: < 40 kg

SSTL MicroSat-100



2. FLORAD micro-satellite system

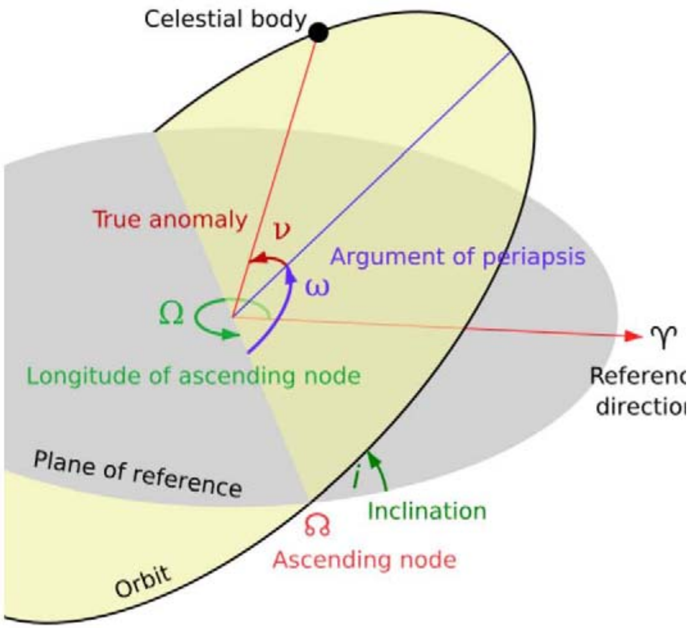
- **Preliminary specifications**
  - Conical scan at 50° incidence angle with ± 45° scan angle
  - Orbit height: 580-620 km
  - Revisit time: < 1.5 h over Southern Europe
  - Antenna reflector: ≤ 40 cm
  - System noise temperature: 1000 K
  - Antenna noise temperature (average): 250 K
  - Average bandwidth: 100 MHz

- **Impact on FLOMIR resolutions**

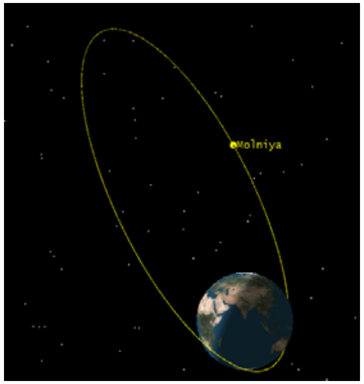
Frequency (GHz)	HP Beamwidth (°)	Field-of-view at 50° (km)	Radiometric precision (K)	Ground swath (km)
50 / 57	1.05° / 0.92°	17.10 / 15.00	0.20	952
89	0.58°	9.61	0.30	952
113 / 123	0.46° / 0.42°	7.56 / 6.95	0.50	952

3. Satellite orbits and constellations

- **Keplerian orbit elements**
  - Inclination i
  - Longitudine of ascending node Ω
  - Argument of periapsis ω
  - Eccentricity e
  - Semimajor axis a
  - Mean anomaly at epoch M_0



- **Weather satellite orbits**
  - Circular (e=0)
    - GEO, equatorial (Clarke, 1945)
    - LEO, near-polar, Sun-synchronous
    - Continuous Whole-Earth Coverage (Walker, 1971)
  - Elliptical (0<e<1)
    - Molniya
      - T=12 h, i=63.4° (to avoid perturbations)



3. Satellite Flower Constellation (FC)

- **Flower constellation theory (Mortari, 2004)**
  - ***Compatible orbits*** (also called *resonant* or *repeating ground track*): set of special orbits whose ***orbital period T*** is synchronized with the period of a *rotating frame with velocity* ω (e.g., Earth-Fixed Earth-Centered).

$$N_p T = N_d \frac{2\pi}{\omega}$$

$$T = 2\pi \sqrt{\frac{a^3}{\mu}}$$

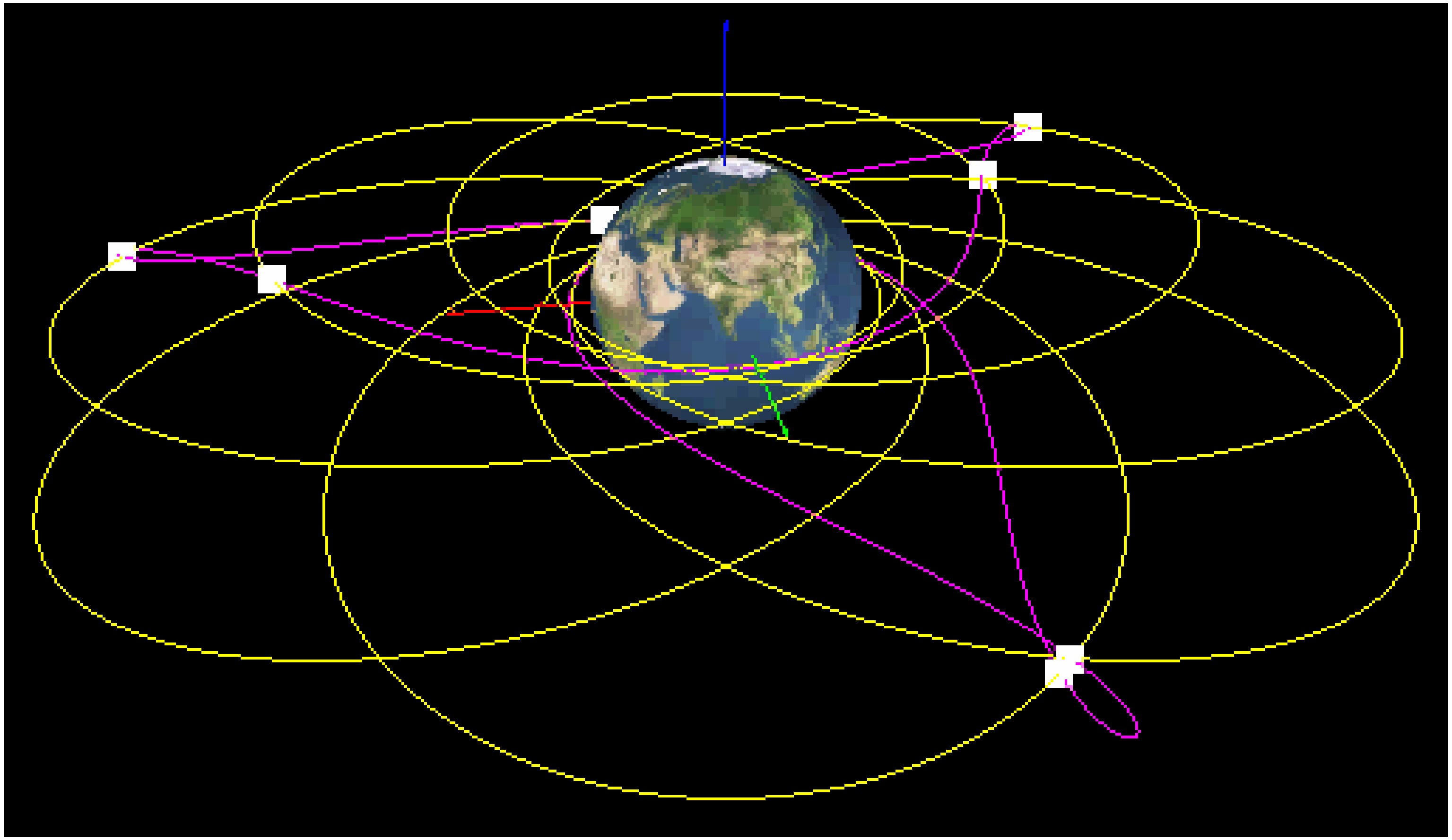
- **FC Phasing rules**
  - ***Trajectory*** in the rotating reference frame (*space track*) constitutes a closed loop with assigned ***repetition time*** T, i.e. satellites run along same 3D trajectory ***one after another***.
    - For the k-th satellite it holds:

$$\Omega_{k+1} = \Omega_k + 2\pi \frac{F_n}{F_d}$$

$$M_{k+1} = M_k + 2\pi \frac{F_n N_p + F_d F_h}{F_d N_d}$$

3. Satellite Flower constellation

- **Example: elliptical equatorial (i=0°, e=0.454)**
  - N_s=6 (# satellites), N_p=3 (# orbit petals), N_d=1 (# days)



3. FLORAD preliminary FC optimization

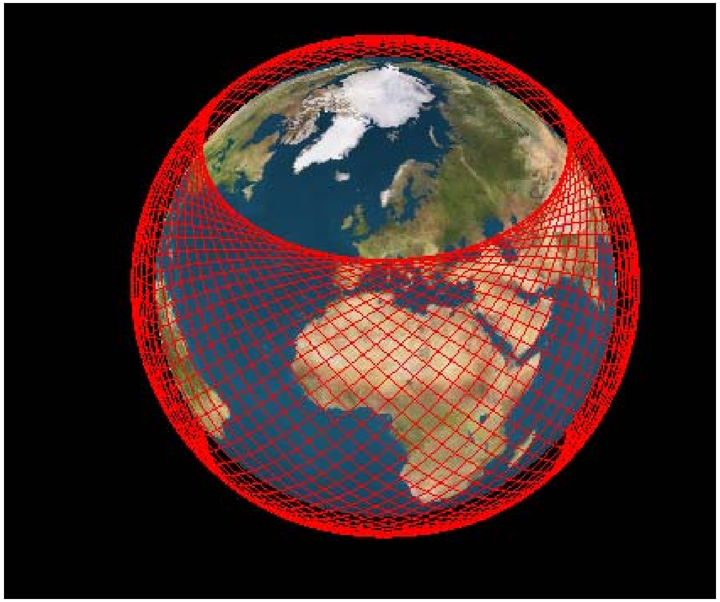
- **Optimized 11 free-parameters through a genetic algorithm**
  - Repeativity over Rome
    - Min= 3 sec
    - Max= 2.5 hours
    - Mean= 1.86 h
    - # access/day = 64

Optimal FC parameters

N_p	59
N_d	4
N_s	4
F_n	1
F_d	4
F_h	0
h_p	620 km
i	44.1°
ω_p	4.779 rad
Ω_0, ($RAAN_0$)	5.992 rad
M_0	0.417 rad

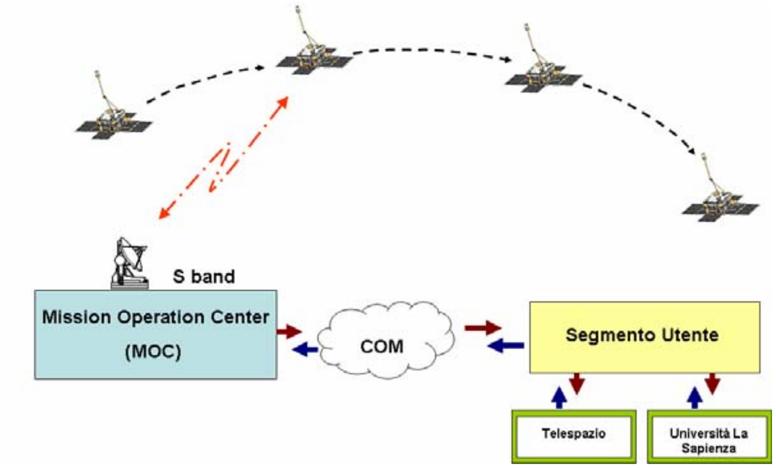
Orbit elements of each satellite with period T=1.61 h

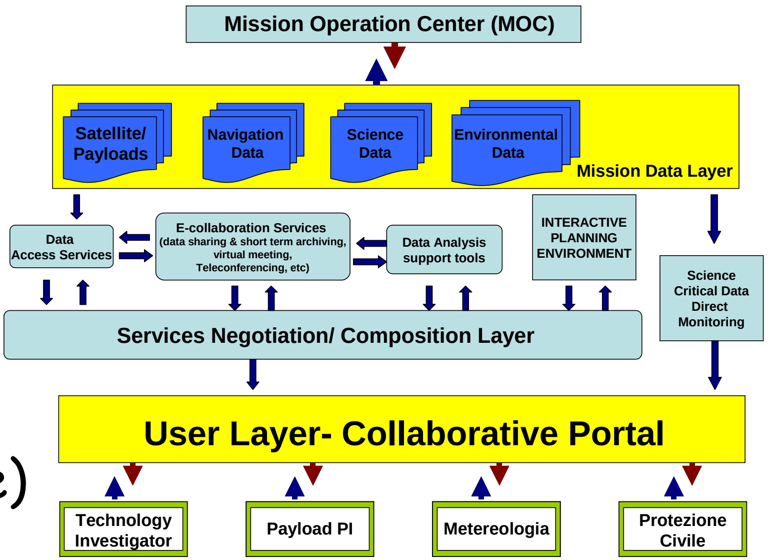
a (km)	e	i (rad)	ω_p (rad)	$RAAN$ (rad)	TA (rad)
7010.49	0.00278	0.769	4.779	5.992	0.417
7010.49	0.00278	0.769	4.779	1.279	2.380
7010.49	0.00278	0.769	4.779	2.850	4.344
7010.49	0.00278	0.769	4.779	4.421	0.024



4. FLORAD Ground segment

- **Mission operations**
  - 4 micro-satellites
  - Data processing and archive
- **Earth stations**
  - S-band , 2 Mbps
  - Telem., Tracking and Command
  - Fucino, Italy
    - Mission Operation Centre
    - Satellite Control Centre
    - Flight Dynamic System
    - Mission Planning System
- **User segment**
  - Distributed architecture
- **Launch support service**
  - LEOP (Launch Early Orbit Phase)
  - Commissioning





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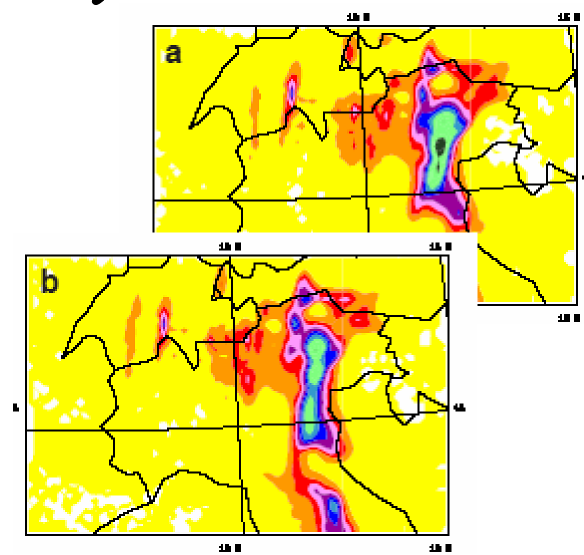
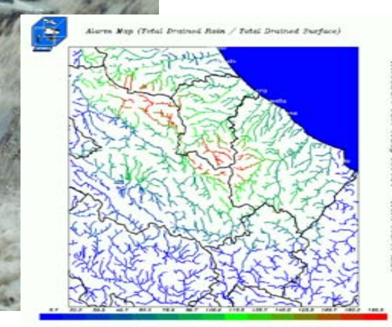
Potential applications of FLORAD

- **Numerical weather prediction (NWP)**
  - Regional non-hydrostatic model
    - Experimental validation
  - Remote-sensing data assimilation
    - Variational techniques
    - Ensemble Kalman filter

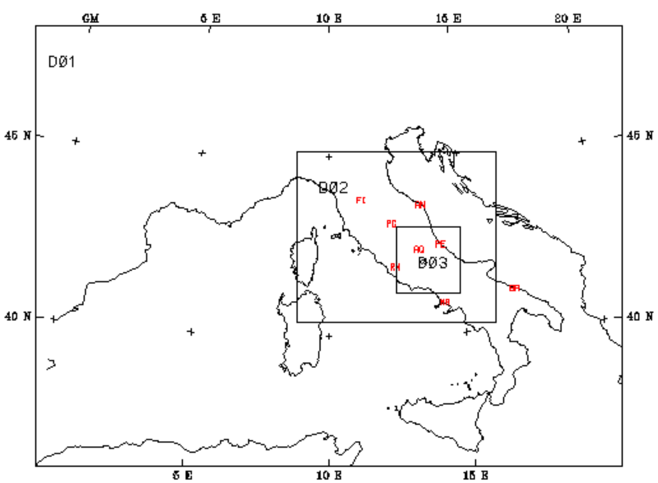


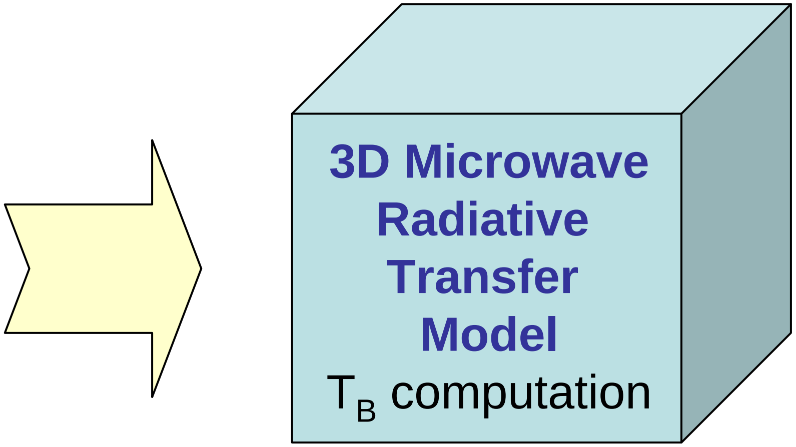
- **Climate change**
  - Legacy of current weather satellites
    - Tropospheric measurements
    - Synergy with other platforms
- **Precipitation nowcasting**
  - Prediction till 2 hours
  - Advection techniques:
    - Eulerian, Lagrangian
  - Applications
    - Civil protection



FLORAD numerical examples

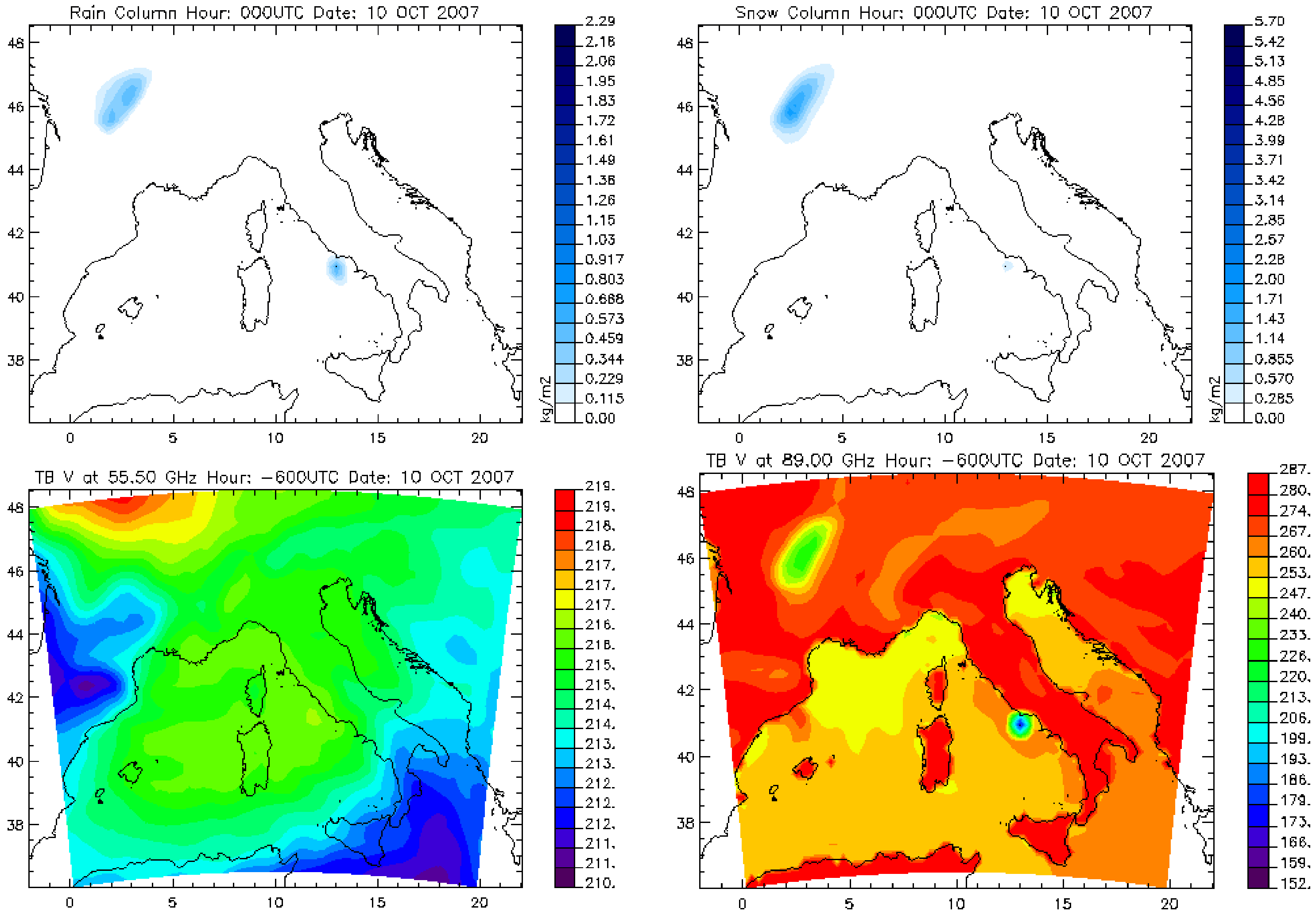
- **Case study on Oct. 10, 2007**
  - Mesoscale Model 5 (MM5)
    - Three-dimensional thermo-dynamical model
    - Non-hydrostatic two-way nested model
      - Larger domain at 27-km resolution
      - smaller domain at 3-km resolution
    - Explicit bulk microphysics
    - Initialization on Global Circulation Model (GCM)





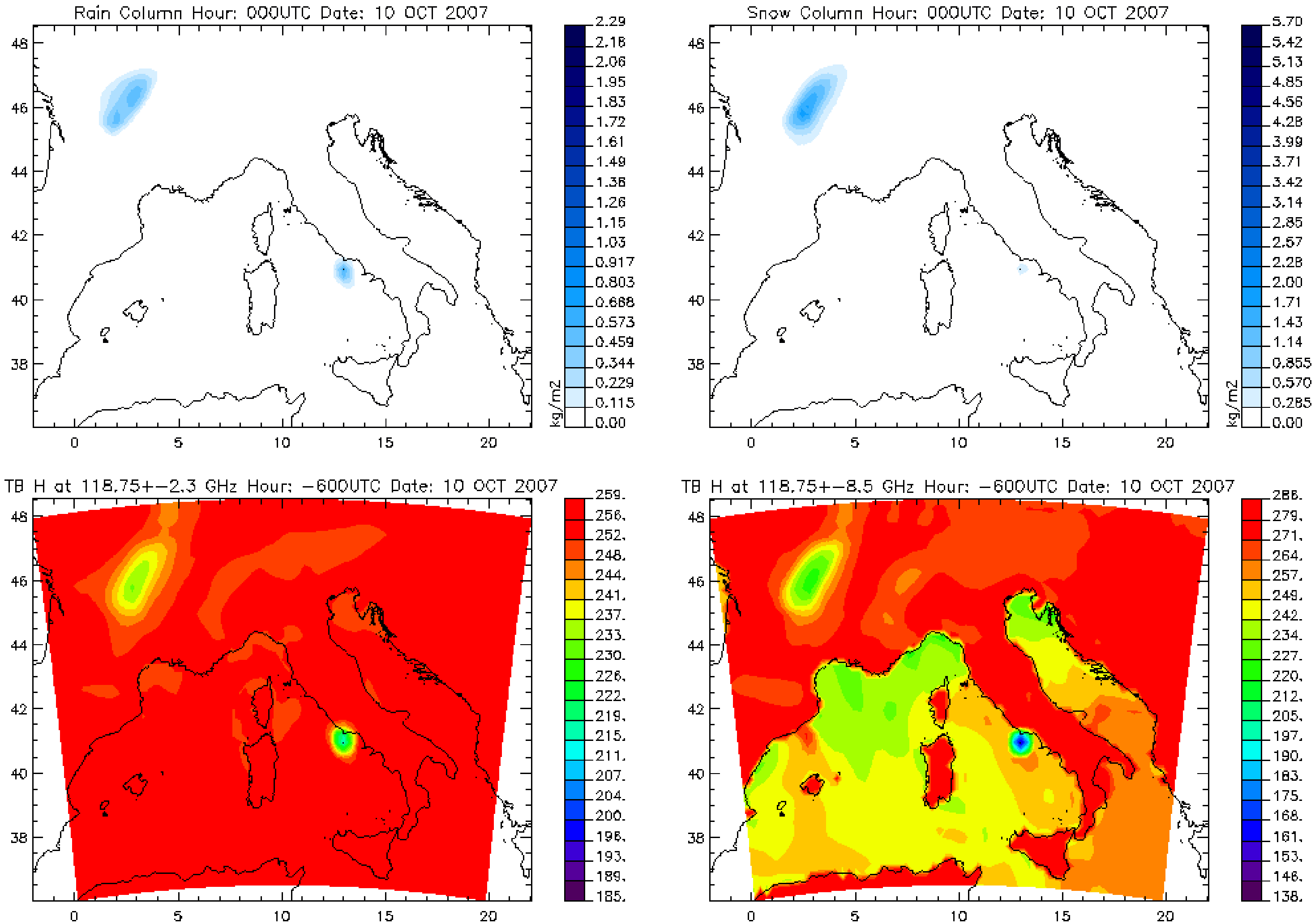
FLORAD numerical simulation: Oct. 10, 2007

- **Satellite T_B at 55.50 V and 89.0 V GHz**



FLORAD numerical simulation: Oct. 10, 2007

- **Satellite T_B at 118.7±2.3H and 118.7±8.5H GHz**



Conclusions

- **FLORAD insights**
  - Increase time repeativity at reg
    - Exploitation of the Flower const
  - Limited budgets of space mission
    - Use of micro-satellites
  - Compatibility between small platforms and paylod
    - Design of compact milliwave radiometers
  - Maximize payload performance/bands
    - Optimization of radiometric channels

  ⇒ **FLORAD mission feasibility study**

- **FLORAD criticalities**
    - Micro-satellites: buy or build them?
    - Launch of 4 micro-satellites with VEGA launcher: feasible?
    - Milliwave radiometer antenna and technology: costly?
    - Flower approach and inversion algorithms: synergy?