An atmosphere monitoring system for the Sardinia Radio Telescope

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Abstract.

The Sardinia Radio Telescope (SRT) is a new facility managed by the Italian National Institute for Astrophysics (INAF). SRT will detect the extremely faint radio wave signals emitted by astronomical objects in a wide frequency range from decimeter to millimeter wavelengths. Especially at high frequencies (>10 GHz), bad weather conditions and interactions between signal and atmospheric constituents (mainly water and oxygen molecules) can strongly affect the radio astronomic observation reducing the antenna performances, for instance, increasing the pointing error or decreasing the sensitivity. Thus, modern ground-based telescopes are usually equipped with systems able to examine in real-time several atmospheric parameters (opacity, integrated water vapor, etc.), and in some cases to forecast the weather conditions (wind, rain, snow, etc.), in order to ensure the antenna safety and support the schedule of the telescope observations. Here, we describe the Atmosphere Monitoring System (AMS) realized with the aim to improve the SRT operative efficiency. It consists of a network of different sensors such as radiometers, radiosondes, weather stations, GPS and some well-established weather models. After a validation of the scheme, we successfully tested the AMS in two real practical scenarios, comparing the AMS outcomes with those of independent techniques. In the first one we were able to detect an incoming storm front applying different techniques (GPS, radiometer and the weather forecast model), while in the last one we modeled the SRT antenna system temperature at 22 GHz processing the AMS data set.

Keywords. Radio telescope, Water Vapor, Numerical Weather Prediction Model, Radiometer, GPS.

1. Introduction

Observing the Universe in different windows of the electromagnetic spectrum greatly improves knowledge of astrophysical phenomena. Radio astronomy observes celestial sources in the radio window, i.e. between tens of MHz and hundreds of GHz. As radio waves are less affected by the atmosphere than other spectral windows, radio telescopes are usually ground-based facilities (located at different altitudes depending on their frequency coverage). In particular, from 10 GHz a radio astronomical observation starts to suffer from the absorption of the water and oxygen molecules present in the atmosphere. This is reflected in two main radio telescope parameters: the antenna gain and the system noise temperature, which are both related to the atmosphere opacity and to the air-mass. For instance, an opacity of 0.1 Np at 20 GHz introduces a reduction in the antenna gain of 10% at zenith and 30% at 15 deg elevation. A similar behavior occurs also in system noise temperature with an extra-contribution due to the atmosphere opacity, which ranges from 25 kelvin at zenith to 90 kelvin at 15 deg elevation.

Therefore, atmosphere monitoring is an important activity performed in a radio telescope site in order to: *i)* characterize the atmosphere parameters at the site, *ii)* support the observation with a real-time monitoring tool, and *iii)* forecasting the weather conditions to schedule dynamically the best experiment with respect to the predicted atmosphere status.

In this paper we present an Atmosphere Monitoring System (AMS) managed at the Sardinia Radio Telescope (SRT) site and able to accomplish these tasks. In section 2 we briefly introduce SRT. Then in section 3 we present the AMS system with a detailed description of its sensors and weather models, while, in section 4, we describe the system validation procedure. Finally, applications for radio astronomy observations and results are discussed in section 5.

2. Sardinia Radio Telescope

The 64-m Sardinia Radio Telescope (SRT[1]) is a general-purpose, fully steerable, wheel-and-track, dual-reflector antenna designed to operate in the frequency range between 300 MHz up to 116 GHz, see figure 1. SRT (Lat. 39°29’34’’N – Long. 9°14’42’’E at 600 m above the sea level) is located 40 km North of Cagliari, the administrative capital of Sardinia. This site has been selected after intensive site testing and characterization campaigns carried out with a microwave radiometer and a geodetic GPS, which demonstrated that the SRT site is suitable for sub-cm observations [1]. Such an investigation was used to measure the effects of the atmospheric constituents and, in particular, the Integrated Water Vapor (IWV) content, which represents the height of the column of water per unit surface that would be obtained if all the vapor in a particular direction in the sky were to condense. The water vapor, due to its high temporal and spatial variability, is the main limiting factor for ground based radio astronomical observations. For instance, in winter, the SRT site has a 40–45% probability of having IWV values below 10 mm. Such conventional thresholds correspond to favorable conditions for centimeter and millimeter astronomical observation.

SRT is equipped with several state-of-the-art devices and modules. This fact, together with its large dimensions, makes SRT one of the most powerful single-dish radio telescopes in the world. One of the most innovative technologies of SRT is the frequency agility, i.e. the capability to switch among the observing bands in a fast and unmanned way, which plays a fundamental role in increasing the antenna performance. Indeed, in the full operational mode, SRT will be equipped with more than 15 radio astronomical receivers

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[1] http://www.srt.inaf.it

to give almost continuous coverage across its operational band. The primary and secondary focus receivers will be hosted in remotely and automatically controlled assemblies.

In 2013, SRT concluded its technical commissioning phase [2]. This phase was performed with three receivers: a coaxial L-P band on the primary focus, a C-band on a tertiary focus and a K-band 7-feed on the Gregorian focus (see the right side of figure 1 for their location in antenna). After that, a coaxial receiver operating in X- and Ka-band was installed and tested for a future utilization of SRT in Space Science [3]. The early science/shared risk observations started in 2016, with a primary mirror alignment of 290 µm, which ensures high efficiency for the receivers currently in operation.

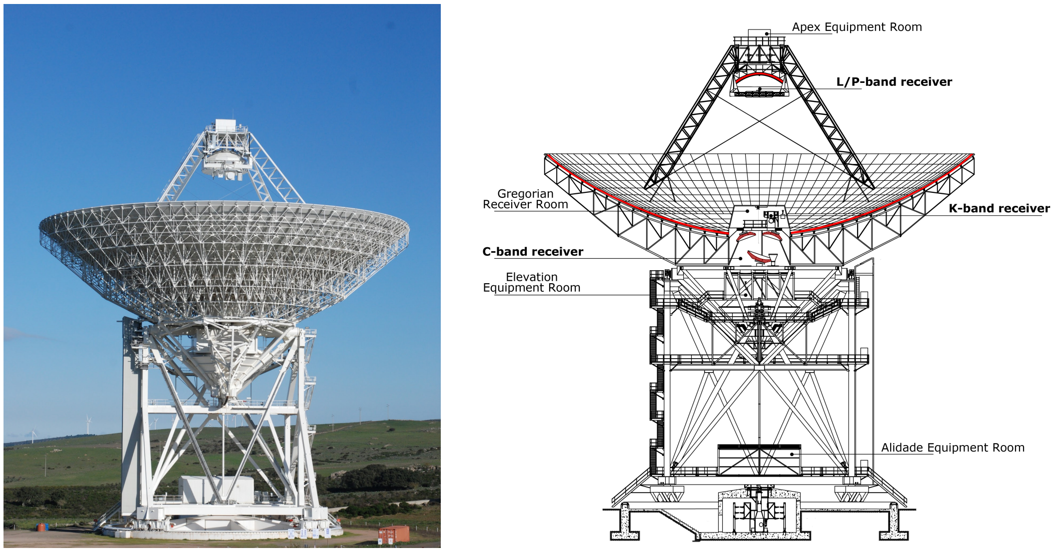

Figure 1. Sardinia Radio Telescope: antenna in stow position (left) and antenna mechanical structure (right), the radiation reflecting surfaces are highlighted in red and the front-end receivers in bold.

3. Atmosphere Monitoring System

In order to support the radio astronomy observations mainly above 22 GHz, where the attenuation due to the H_2O resonance strongly affects the incoming radiation, SRT has been provided with a distributed atmospheric monitoring and forecasting system, whose schematic representation is shown in figure 2.

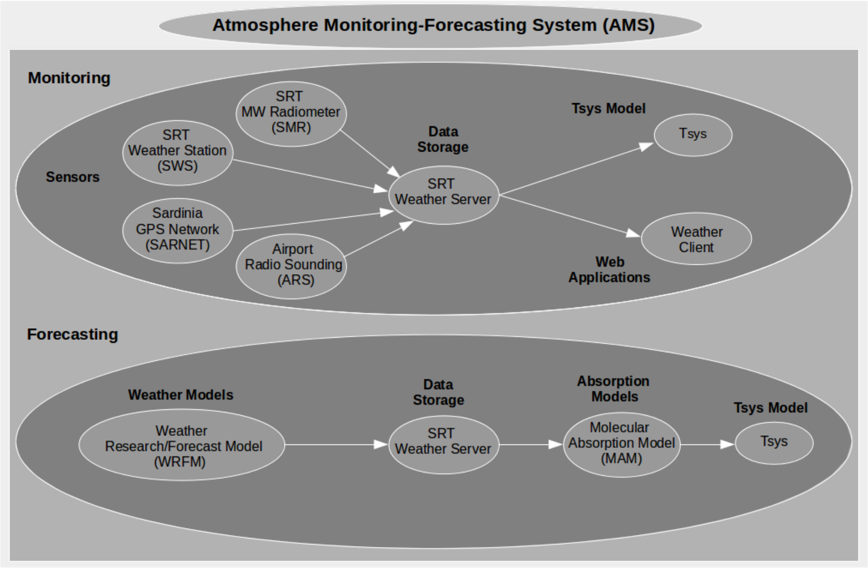

Figure 2. Schematic representation of the AMS.

The AMS uses data sets coming from local sensors, such as the SRT Microwave Radiometer[2] (SMR) and the *in situ* SRT Weather Stations (SWS), from a Regional GPS Network (SARNET) managed by a private company[3], and finally from an Airport[4] Radio Sounding (ARS) site to perform a real-time monitoring of the atmosphere status, see top panel in figure 2. All measured and derived data, i.e. opacity, brightness temperature, IWV, Integrated Liquid Water (ILW), temperature vertical profiles, and thermodynamic parameters are sent daily to a SRT weather server. There, they are saved and then made available, by means of a weather client, to the telescope operators for the antenna safety and to researchers for the calibration of the observations.

In addition, the SRT server daily receives the output data of an accurate weather forecast model (WRFM[5]) managed by the agency responsible for the regional hydro-weather forecasts, ARPAS[6], see bottom panel in figure 2. The WRFM output provides a reliable forecast of opacity, brightness temperature and the water molecule concentration, in the atmospheric layers over the SRT site. AMS processes WRFM data to derive the absorption coefficients for each single molecular species in atmosphere, by using a well-established Molecular Absorption Model (MAM) [4,5].

The MAM data are used in a procedure to calculate the system input noise temperature, which is the sum of two contributions: the receiver noise temperature and the antenna noise temperature. In particular, the latter is calculated by knowing the far-field radiation pattern and the sky brightness temperature. In our procedure, we calculate the far-field radiation pattern by using a commercial electromagnetic software[7], whereas the brightness temperature is either derived directly from SMR data, or calculated independently by ARS or WRFM data. In the first case, we get a T_{sys} monitoring, in the second one we are able, by using WRFM data, to forecast T_{sys} with even 36 hours in advance.

In the following section, each monitoring sensor and each forecasting model will be described in detail.

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[2] Radiometrics M-3000A (http://radiometrics.com/)
[3] http://www.sarnet.it
[4] Cagliari-Elmas air force base (LIED) located about 30 km far from SRT site
[5] http://www.wrf-model.org/
[6] http://www.sar.sardegna.it/
[7] GRASP by TICRA, http://www.ticra.com/products/software/grasp

2.1. SRT Microwave Radiometer

The SMR is an accurate instrument able to perform azimuth-elevation scans of the atmosphere in 32 channels distributed in two frequency bands: K-band from about 20 to 30 GHz and V-band frequencies from about 50 to 60 GHz. In K-band, SMR mainly retrieves the IWV and ILW, while at V-band it retrieves the vertical temperature profiles. It is worth noting that SMR measures the sky emission in voltage units, but through calibration and an appropriate transfer function, it gives a good estimation of the brightness temperature in Kelvin degrees.

2.2. Radiosondes

In atmosphere science, radiosondes are commonly considered as reference instruments for the calibration of weather models and remote sensors (for instance, microwave radiometers). Indeed, during their ascent to the higher layers of the atmosphere, the radiosonde may indirectly measure absorption (opacity), brightness temperature and IWV. These observations together with the radiosonde position, measured by the on-board GPS receiver, are continuously transmitted to a ground receiver. However, radiosondes are by no means perfect instruments, providing a limited number of observations per day and their sensors being often characterized by systematic errors, as in the case of the humidity sensors that may be affected by systematic bias problems [6].

The ARS are launched twice a day about 30 km far away from the SRT site. In principle, this distance is acceptable considering that these kinds of sensors during their ascent can move horizontally by as much as 50 km from the initial launch position. Nevertheless, Cagliari-Elmas airport is located at sea level between the sea and a lagoon, so measurements, especially in the first few hundred meters, are probably affected by the local micro-climate effects.

Recently, we made a statistical study considering a long data-set of radio soundings [7], which gave useful information on which period of the year and of the day astronomical observations at different frequencies should be preferably performed.

2.3. Weather stations

Three SWSs operate within the area close to the telescope. Each SWS consists of an ultrasonic anemometer, a rain gauge, a pressure sensor, and a temperature and humidity transducer. These are very important instruments for measuring the ground level geophysical quantities, for instance the wind speed. Indeed, the monitoring of wind speed is critical for antenna safety and for evaluating the radio telescope tracking errors. Inaccuracies in the antenna pointing may lead to signal strength attenuation, mainly at high frequency at which the pointing accuracy is a more strict constraint.

2.4. Sardinia GPS network

The GPS receiver cannot directly measure atmosphere parameters, but in a GNSS network some biases related to atmosphere are estimated to accurately assess the station coordinates. Among those biases, there is the signal delay along the troposphere. When a GPS signal crosses the atmosphere, it experiences a delay, called tropospheric delay, which depends on the refractive index of the crossed medium. Tropospheric delay varies in space and in time so, to solve for this bias, the slant delays from each satellite and for each station are projected, through a mapping function, along the vertical direction. Therefore, a single Zenith Troposphere Delay (ZTD) is estimated for each station, usually every hour. The ZTD can be separated in two components: a dry (hydrostatic) component and a wet component. The former is due to the dry gases and is denoted as Zenith Hydrostatic Delay (ZHD), the latter is due to the water vapor refractivity, and is denoted as Zenith Wet Delay (ZWD).

Since the ZTD is the only observable directly achievable by GPS the technique, in order to derive the ZWD, and consequently the IWV [8], it is necessary to estimate independently the hydrostatic part to be subtracted from the ZTD. The ZHD may be computed by means of the Saastamoinen model, knowing the latitude and the station height, together with the barometric pressure at the antenna position [8].

The ZTD is becoming an important parameter in atmospheric science, because the GNSS permanent network is distributed densely worldwide nowadays. Moreover, new tropospheric products obtained by the Networks for Real-time Kinematic (NRTK) services are now available with higher spatial and temporal resolution. The use of these new advanced tropospheric products has been advised by both the climatic and geodetic science communities[8], in order to fully exploit their potentiality for real-time monitoring and forecasting of severe weather.

Following this research field, we have included the NRTK SARNET in AMS. Active since 2006, SARNET consists of 13 GPS stations homogeneously distributed over the Sardinian island with mean mutual distances of about 60 km, see figure 3. All stations are equipped with dual frequency Trimble receivers and antennas linked to a Control Centre, settled in Cagliari, via DSL connection. All receivers are configured to provide services for precise NRTK positioning with a sampling interval of 1 Hz.

The Control Centre includes a central processing unit in which the Trimble GPSNet software processes receiver data on an epoch by epoch basis in order to create correction streams for field users [9]. In addition, the software archives reference station data and atmospheric biases (zenith ionospheric and tropospheric delays), for post processing services. A new ZTD value is available every minute at each station.

2.5. Weather models

We use a state-of-the-art local area model (LAM), WRFM, on a daily basis to provide SRT with the forecast of the opacity, brightness temperature, IWV and ILW.

The forecast area ranges from 6.9° to 11° East and from 38.3° to 41.6° North, including the Sardinia Island, and defines a grid of 217×219 points with a spatial resolution of about 2 km. Moreover, 45 vertical levels above the ground of this area and 36-hours forecast are usually considered.

Since each model produces a large amount of data, the time resolution and the number of the vertical layers are reduced. Only about 250 MB data are stored and sent to a server hosted in OAC, where they are processed. They include 13×3-hours epochs and 19 vertical layers (from 1000 to 100 hPa) and only a few parameters, the most interesting ones for our application.

In the centimeter and sub-centimeter wavelength range only rotational transitions must be taken into account and only O_2 and H_2O give a remarkable contribution to the absorption [4,5]. Then, the AMS extracts only these absorption coefficients from the WRFM dataset.

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[8] http://www.cost.eu/COST_Actions/essem/ES1206

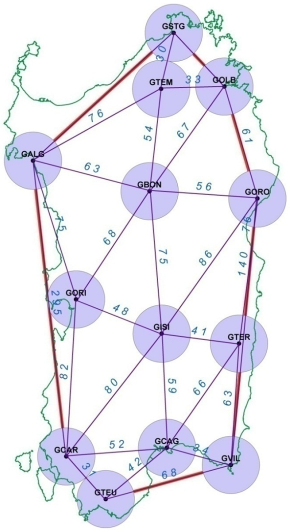

Figure 3. Sardinia GPS Network (SARNET).

3. System validation

In the last years, we extensively tested the feasibility of the AMS [10]. In this section, we present two cases, as an example of our activities related to the study and characterization of the atmosphere of SRT site.

3.1. Integrated water vapor survey

Radiometer, radiosondes and GPS are quite different measurement techniques, based on different physical principles. When IWV measurements obtained by different approaches are compared, it is mandatory to distinguish between site and measurement technique related effects. This is especially true for the radiosondes, as the launching sites (usually airports) may be very far away from the sites of interest. Radiosondes are often considered to be a reference technique being able to give a direct measurement of the quantities of interest. The most relevant drawback of this technique is that only a few measurements per day are available, while radiometers and in some cases GPS are able to provide non-stop IWV measurements in real-time. In 2009, we installed the SMR and a geodetic GPS antenna-receiver pair at the radiosondes launching site, the Cagliari-Elmas airport[9]. The instruments operated continually for seven months from April to October 2009.

The SMR and the GPS were installed on the roof of the Aviation Weather Center at Cagliari-Elmas airport, see figure 4. The obtained GPS ZTD time series were separated into the dry and wet parts and, then, the IWV was calculated. The weather station hosted on the SMR provided the weather data, necessary to separate the dry and wet components.

IWV may be calculated retrieving the specific humidity from radiosonde data and integrating this quantity numerically along the radiosonde path. In our case, there were two launches per day corresponding to 0 and 12 UTC.

In table 1, the standard error (Stderr), the bias and the correlation (Corr) obtained from the data analysis are shown. Due to the different size of data sets, the comparison should be made with care, but it is evident that the best agreement is obtained comparing SMR with GPS data. It is worth noting that summer is the season showing the highest IWV variability, causing poorer agreements with GPS, while in the cooler seasons the

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[9] Recently the radiosonde launch site has been moved to the Decimomannu airbase, LIED, 39° 21' 11" N, 08° 58' 26" E.

agreements tend to be better [6]. The last column in table 1 reports the SMR versus GPS parameters estimated, in the same season, in a previous campaign carried out in South Sardinia [1]. The good agreement with these results gives us confidence in the assessment of SMR as a reference probe for GPS data.

Figure 4. Co-location experiment site: GPS antenna (left) and radiometer (right).

Table 1. IWV co-location survey statistical analysis.

	ARS vs SMR	ARS vs GPS	SMR vs GPS	SMR vs GPS [1]
Samples	99	61	567	245
Stderr (mm)	2.5	3.3	1.9	1.7
Bias (mm)	1.2	-0.1	-1.0	-0.7
Corr	0.952	0.838	0.943	N.A.

3.2. SARNET validation

As previously stated, AMS exploits the capability for a GNSS NRTK software to estimate real-time ZTD. The advantages in using GNSS sensors are a much lower cost of instrumentation and the assessment of spatial distribution for the ZTD.

The research activity involves the study of the following topics: *i)* validation of real-time ZTD estimates produced by Trimble GPSNet software, *ii)* retrieving and validation of IWV from ZWD, and *iii)* realization of a recording, processing and displaying framework for the content of water vapor maps on a regional scale.

Since GPSNet is a commercial software not designed for our purposes, we had to assess the reliability of ZTD estimates in real-time, performing a complete reprocessing of GPS data with Bernese software[10], by applying EUREF[11] processing strategies for tropospheric estimates. We had to redesign the network adding more distant stations, in order to de-correlate the spatial tropospheric biases. In the final configuration the network included the thirteen SARNET stations, SRT1 (SRT site GNSS station), nine GNSS stations belonging to the IGS network and six stations belonging to the EPN. The data re-processing covers a time interval of roughly six years between 2007 and 2013. The tropospheric parameters obtained are in very good agreement with those directly processed, for the shared stations, by the EUREF Analysis Centres, showing a mean correlation of 0.99.

After that, we compared the ZWD Bernese estimates with those recorded by the GPSNet software, estimated in real-time. Table 2 shows the correlation, the standard error and the bias as obtained after our analysis comparing the Bernese output (considered as reference) with the GPSNet, the WRFM and the "wet" Saastamoinen model [8] outputs respectively. The analysis was carried out for all the thirteen stations forming SARNET. The agreement between the Bernese-GPSNet and the Bernese-WRFM time series analysis is very promising and it is quite compatible with the SRT operative requirements. The agreement with the Saastamoinen model is poorer, being only based on ground level observations.

Table 2. SARNET IWV statistical analysis.

Station	Cor WRFM-BER	Cor GPS-BER	Cor SAA-BER	Stderr WRFM-BER	Stderr GPS-BER	Stderr SAA-BER	Bias WRFM-BER	Bias GPS-BER	Bias SAA-BER	Samples
GALG	0.919	0.905	0.726	3.0	3.7	8.0	-0.6	0.7	-5.4	3163
GBON	0.889	0.890	0.721	3.2	4.0	5.4	0.0	1.0	-2.8	2773
GCAG	0.921	0.914	0.748	3.5	4.0	8.4	-1.6	1.5	-5.9	2624
GCAR	0.909	0.892	0.703	3.6	4.1	5.9	2.0	1.8	-1.4	2590
GISI	0.908	0.897	0.711	3.2	4.0	5.6	1.2	0.9	-2.4	1892
GOLB	0.926	0.920	0.779	3.1	3.7	5.5	0.0	0.7	-1.8	3355
GORI	0.921	0.903	0.727	2.9	3.7	6.0	-0.1	0.5	-2.6	1539
GORO	0.917	0.923	0.803	3.5	4.0	5.9	1.1	1.0	-2.2	2549
GSTG	0.915	0.905	0.731	4.1	3.8	5.9	2.7	0.9	-1.2	1793
GTEM	0.913	0.897	0.733	4.3	3.7	8.0	-3.2	0.6	-6.3	2308
GTER	0.913	0.922	0.795	6.4	4.0	5.9	5.5	1.3	2.9	2649
GTEU	0.909	0.898	0.710	7.6	3.8	6.7	7.0	0.5	3.6	2662
GVIL	0.915	0.912	0.750	3.2	3.9	7.3	-0.5	1.2	-4.7	3321

4. Results

In this section, we describe two practical cases of the exploitation of AMS, which show the usefulness of the system to predict the atmospheric conditions and, hence, the weather condition for the success of an astronomical observation.

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[10] http://www.bernese.unibe.ch/

[11] http://www.epncb.oma.be/

4.1. Storm front approaching SRT

During a radio astronomical observation the atmospheric conditions may quickly vary causing a potential reduction of the intensity of the incoming radio signal. In figure 5 we report two images of the NOAA-19 weather satellite, acquired on January 24, 2010, showing an incoming storm front approaching the south west of Sardinia Island at 11:54 a.m. (left panel) and reaching the SRT site at 1:35 p.m. (right panel).

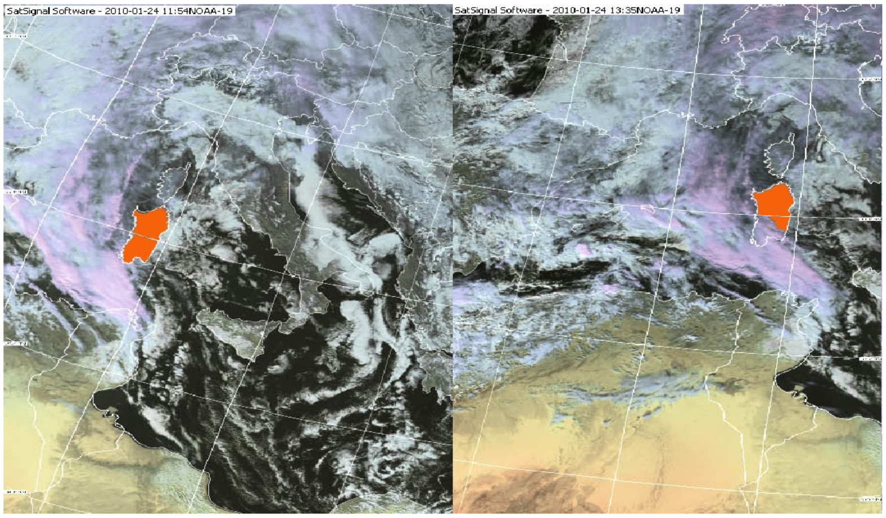

Figure 5. Two NOAA-19 weather satellite images showing an incoming storm front approaching the South Western Sardinia on January 24, 2010 at 11:54 a.m. (left panel) and over the SRT site at 13:35 (right panel).

Due to such a storm front the IWV at the SRT site increased (from 6 to 18 mm) in less than 12 hours, as a consequence of the injection of moist air, and the atmospheric conditions became suddenly unfavorable for K-band observations.

The IWV variation was well detected by the SMR and the GPS in real-time and the WRFM-LAM was able to predict this event one day in advance (see figure 6). Indeed, figure 6 shows very good agreement between the IWV data measured at the same epoch by the radiometer (black curve), GPS (blue curve) and forecasted by the WRFM-LAM (red curve). In this case, the antenna operator would have been able to schedule the proper experiment with respect to the atmospheric conditions one day in advance. This example clearly demonstrates that an accurate weather forecast is particularly useful in order to improve the efficiency of the scheduling of a modern radio astronomical facility and, more generally, becomes essential for the implementation of a dynamic scheduling system, i.e. observations scheduled accordingly to the incoming atmospheric conditions.

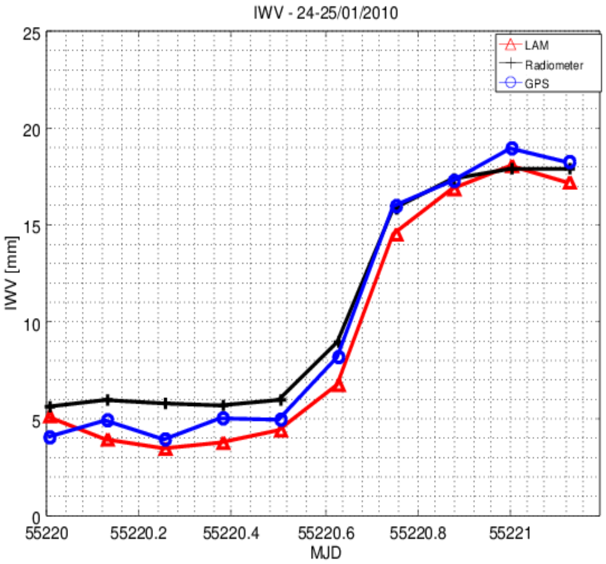

Figure 6. IWV measured (radiometer and GPS) and forecasted one day in advance (WRFM- LAM) in January 24-25, 2010.

4.2. System Temperature Measurements with SRT

Skydip is an observation strategy commonly used in radio astronomical data calibration. It involves the measurement of system temperature by means of an angular elevation scan, therefore, by using the radio telescope as a radiometer. The obtained signal (as a function of the elevation angle) depends on the sky brightness temperature and it is useful to directly measure the sky opacity and other relevant parameters.

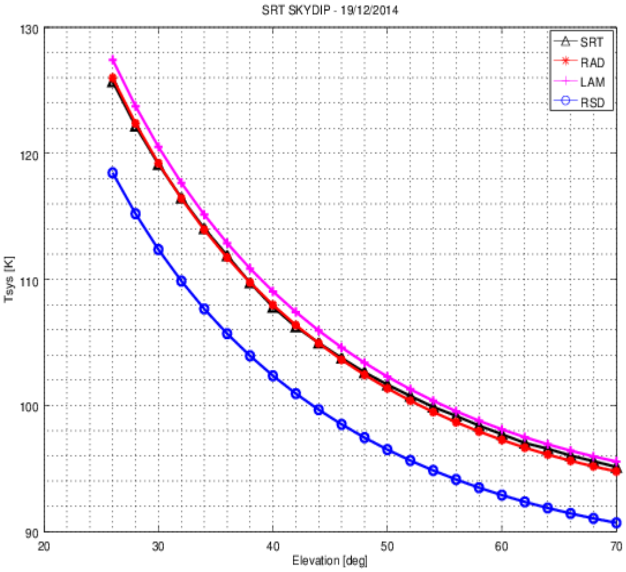

Figure 7. Comparison of the T_{sys} by a K-band (22 GHz) skydip (black curve), by radiometer monitoring (red curve), by weather forecasting model (magenta curve) and by radiosonde (blue curve).

In figure 7 a K-band T_{sys} obtained by a SRT skydip is compared with the T_{sys} by radiometer, WRFM-LAM and radiosondes. The curves show the typical monotonic behavior expected due to the fact that the signal crosses different air masses during the scan (the system temperature reaches the minimum at the zenith). It is noteworthy that where both the WRFM forecast and the SMR measurements are in good agreement with the SRT data, instead the radiosonde data underestimate the "true" antenna system temperature. This is not surprising, as the radio soundings are available only twice-per-day. This time resolution is not enough to take into account the high variability of the atmospheric IWV.

5. Conclusions

A distributed and composite system made up of different sensors has been integrated and installed at the SRT site for both measuring in real-time and forecasting the atmosphere parameters. This system allows the antenna operator to have a figure of the expected atmosphere and, thus, to take a decision on which is the best astronomical observation to run. We discussed two basic applications to real cases showing the reliability of the system in predicting the atmospheric conditions, as support to a dynamic scheduling of the SRT.

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