Experimental Validation of VOR (VHF Omni Range) navigation system for stratospheric flight

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Abstract

This paper presents the results of STRATONAV experiment to test the precision of the VOR (VHF Omni Range) aircraft navigation system in stratosphere. The experiment has been conducted by the S5Lab research group at Sapienza University of Rome in the framework of the REXUS/BEXUS Programme. STRATONAV has been successfully launched on-board the BEXUS 22 stratospheric balloon from Esrange Space Center in Kiruna, Sweden, in 2016. The main payload was composed by two typologies of VOR receivers, a commercial portable receiver and a Software Defined Radio (SDR), alongside the bus and positioning, attitude and temperature sensors. STRATONAV succeeded in collecting VOR radials for the whole duration of the balloon flight. The results prove that VOR can be used as back-up navigation system for stratospheric platforms, ensuring a reliability improvement, while being applied to smaller payloads as primary system for a cost and complexity reduction of experiment developments. The paper analyzes the collected VOR data during the balloon flight. Accuracy and performance plots with respect to distance from the VOR stations and altitude are presented and discussed. The mean errors and standard deviations from all stations for both the receivers are shown with an analysis over the recorded errors. Finally, future perspectives, analyses and applicability of the research are exposed.

Keywords

Stratosphere, radio, navigation, VOR, balloon, SDR

List of Acronyms

AIP	Airport Information Publication
AM	Amplitude Modulation
ANSP	Air Navigation Service Provider
ASL	Above Sea Level

BEXUS	Balloon-borne Experiments for University Students
COTS	Commercial Off The Shelf
DLR	German Aerospace Center
ESA	European Space Agency
FIR	Finite Impulse Response
FM	Frequency Modulation
GNSS	Global Navigation Satellite Systems
GPS	Global Positioning System
HAPS	High Altitude Platform Stations
HVOR-NAV	High Altitude VOR Stations for Navigation
ICAO	International Civil Aviation Organization
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
NAV	Navigation
NavAid	Navigational Aid
OBC	On-Board Computer
OBDH	On-Board Data Handling
PCB	Printed Circuit Board
RF	Radio-Frequency
S5Lab	Sapienza Space Systems and Space Surveillance Laboratory
SDR	Software Defined Radio
SNSA	Swedish National Space Agency
SSC	Swedish Space Corporation
SSD	Solid State Drive
SSV	Standard Service Volume
STRATONAV	Stratospheric Navigation Experiment
TARDIS	Tracking and Attitude Radio-based Determination in Stratosphere
UTC	Universal Coordinated Time
VHF	Very High Frequency
VOR	VHF Omni Range
ZARM	German Center for Applied Space Technology and Microgravity

1. Introduction

The Very High Frequency (VHF) Omni Range (VOR) is a mature and reliable aircraft radio-navigation system, used for decades to route aircraft towards its destination and still in service for the civil aviation. The system is based on a network of ground stations transmitting a complex signal containing three main components:

- the ID of the station, a three-letters code transmitted in Morse seven times per minute;
- a reference signal, indicating the magnetic North direction;
- a directional signal, whose phase changes with respect to the transmitting Azimuth direction [1].

The reference and directional signals are 30Hz sine waves characterized by a phase shift proportional to the aircraft bearing angle with respect to the ground station. The VOR receiver is a passive system that shall de-modulate the signals and compute the phase shift in order to obtain the bearing, commonly called "radial". The standard accuracy of the system in determining the radial was originally ±4 degrees [2], while the modernly conceived ground stations are able to achieve a ±1.4 degrees standard radial accuracy rate [3]. Although being considered mostly a back-up navigation system, VOR assures the achievement of the needed reliability rates for a safe navigation, being also the only passive radio-navigational aid (i.e. not foreseeing the airborne device to transmit). The system is often coupled with Inertial Navigation Systems (INS) and Global Navigation Satellite Systems (GNSS) [4,5]. Its operational range is defined by the International Civil Aviation Organization (ICAO) with the received power density operational threshold of -107 dBW/m^2 [1]. By considering the station usage (terminal or high/low altitude navigation VOR) and the regional topography, the Air Navigation Service Providers (ANSPs) define each station Standard Service Volume (SSV) in the Airport Information Publication (AIP) documentation, that shall take into account high safety margins for ensuring high service reliability for civil aircraft of all classes. High Altitude Navigation VOR stations (HVOR-NAV) are usually characterized by a 200 W emitted power ([3]), and their SSV is defined as a cylinder of radius 185 Km (100 NM) and height 16700 m (55000 ft) ([6–8]). However, power density and link budget calculations [9] demonstrate how acceptable power densities could be achieved beyond the current commercial aviation limit altitude for stratospheric vehicles even when considering the highest loss rates possible. The availability of the service is usually monitored by conventional fixed-wing aircraft [10], with a consequent impossibility to verify the VOR accuracy flying nearby its approximated limit height. An experimental investigation on VOR accuracy in stratospheric flight can confirm the service availability and accuracy rates for the future stratospheric aviation. VOR can be indeed applicable as navigation system of the rising concepts of stratospheric platforms and airships [11–14], able to provide quasi-satellite tasks at lower development, launch and operational costs [15–18].

This paper deals with the results of the STRATONAV Experiment, developed in 2016 at Sapienza University of Rome by a team of Italian aerospace engineering students and launched in October 2016 from the Esrange Space Center in Kiruna (Sweden) in the framework of the REXUS/BEXUS Programme (managed by SNSA, Swedish National Space Agency, DLR, German Aerospace Center and ESA, European Space Agency, [19]).

After an introduction on the fundamentals of the VOR system and an overview of the STRATONAV experiment architecture, the results are discussed. Finally, the conclusions report the possible applicability and extensions of the conducted study.

2. The STRATONAV Experiment

STRATONAV (STRATOspheric NAVigation) is a scientific project conceived in late 2015 by an Italian university student team from Sapienza University of Rome and Alma Mater Studiorum – University of Bologna. The project was selected in 2015 for the REXUS/BEXUS Programme. The STRATONAV experiment was developed at S5Lab (Sapienza Space Systems and Space Surveillance Laboratory) between January and September 2016. It was launched on the BEXUS 22 stratospheric balloon from Esrange Space Center in Kiruna (Sweden) on October 5th, 2016. The experiment aimed at testing the VOR accuracy rates above its SSV (Standard Service Volume) end. The objectives are connected to the potential usage of the VOR as navigation system for stratospheric vehicles. The target accuracy rates for the experiment are the ICAO accuracy standard value offered by the first generation of VOR ground stations, equal to ±4 degrees of error in the radial determination. The experiment objective was conceived by assuming as acceptable and safe a degradation of the service due to increased distance and height (the current standard precision is ±1.4 degrees, as reported in Section 1) that would not overcome the standards used for routing civil aircraft for decades.

The student team oversaw of the experiment design, from the environmental control for low air density and temperature to electric power budgets and telemetry communication protocol concept. The experiment was designed, developed and qualified for the stratospheric flight between January and September 2016, with several reviews from the organizing agencies' experts.

In order to perform the precision rate verification, STRATONAV included two VOR receivers:

1. a Commercial-Off-The-Shelf (COTS) VHF transceiver, equipped with VOR radial evaluation tools [20];
2. a Software-Defined Radio (SDR), able to record signals throughout the dedicated VOR VHF band [21].

While the described COTS receiver was able to calculate the radial in real-time, the SDR data required further processing in the post-flight analysis to reveal the received VOR signals and the evaluated radials. A schematization of the RF system illustrating data and command lines is presented in Fig. 1.

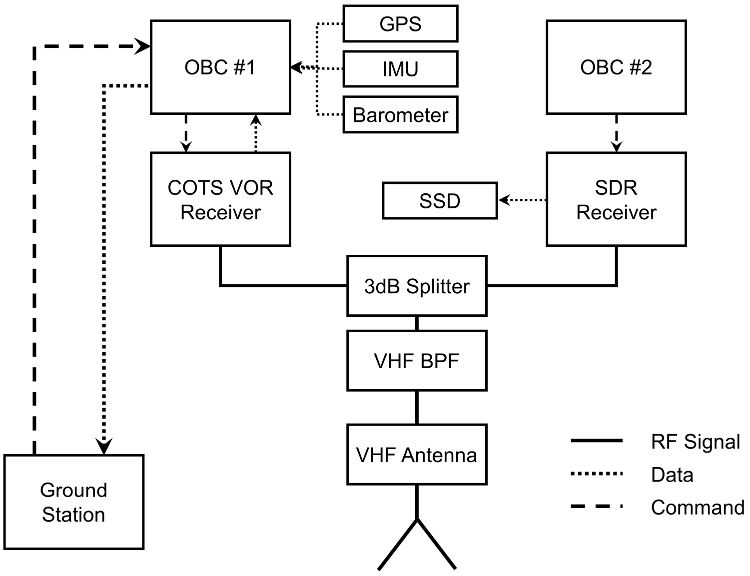

Fig. 1: STRATONAV instrumentation architecture.

Both the receivers were connected to the experiment RF receiving chain, composed of a 3dB splitter, used to provide both the receivers with a signal, of a VHF-Navigation band filter, applied to avoid any FM-radio inter-modulation interferences or disturbances from electro-magnetic transmitting devices on-board the balloon (that allocated four university experiments), and of a V-shaped bespoke antenna, that replicated the geometry and the performances of a traditional VOR antenna usually mounted on general aviation planes equipped with VOR receivers.

Every RF receiver was connected to a dedicated computer, able to control it and store the collected data. The first On-board Computer (OBC #1) was connected to the COTS VOR receiver. The OBC #1 was able to switch the receiver's frequency by digitally controlling the keypad through a multiplexer system. The VOR radials computed by the COTS receiver were accessed directly from two analog lines of the receiver, extracting the reference and directional sine waves described in Section I and computing their phase shift for acquiring the radial, and through a back-up camera system periodically acquiring images of the receiver screen. Reference positioning and attitude data were collected from a GPS (Global Positioning System) and an IMU (Inertial Measurement Unit) connected to OBC #1 and stored on-board. A barometer provided back-up altitude information, needed for automatic shut-down of the experiment during the descent phase for safety purposes. The first OBC was also connected to the experiment Ground Station via the balloon telemetry system, allowing telemetry downlink and telecommand uplink when needed. OBC #2 was connected to the SDR receiver to command and support the recording operations of the VHF VOR band. All the recordings were stored in a Solid State Drive (SSD) for post-flight analysis.

The set of scientific tools and instrumentation was integrated inside an aluminum box of approximately 340 x 340 x 550 mm, upholstered with high performance insulating material to protect the components from the challenging environmental conditions. The whole experiment mass was 12 kg. Pictures of the box and installed components, of the V-shaped antenna and of the whole system integrated on the BEXUS gondola are shown in Fig. 2, Fig. 3 and Fig. 4.

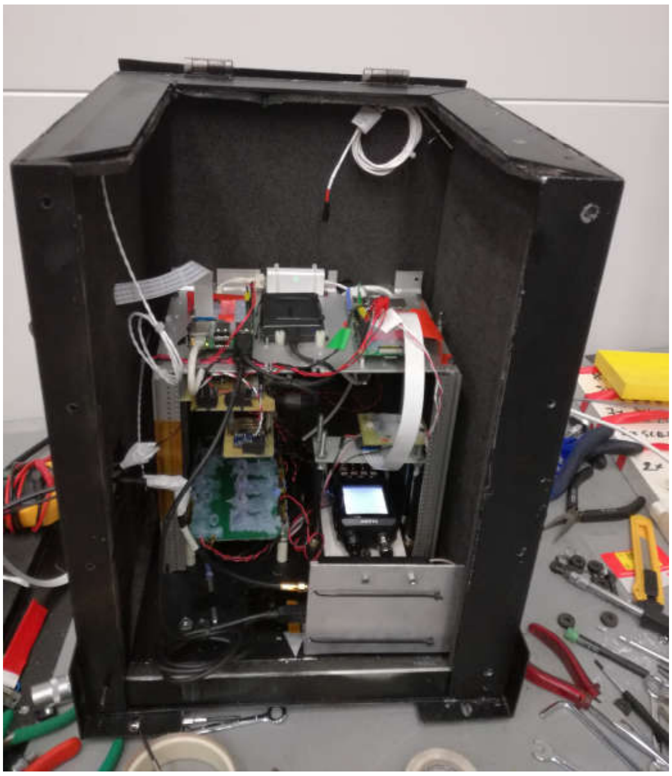

Fig. 2: The STRATONAV Experiment box.

Fig. 3: STRATONAV VHF VOR antenna.

Fig. 4: STRATONAV integrated on the BEXUS 22 gondola during the functional tests.

The BEXUS 22 stratospheric balloon was launched on October 5th, 2016, at 13.33 UTC from the Esrange Space Center in Kiruna (Sweden). A picture of the balloon flight train at launch is presented in Fig. 4. The balloon completed its ascending phase by reaching the floating altitude of 32.3 km at 15.21 UTC. The floating phase ended with the balloon cut-down at 17.41 UTC and the balloon landed after a parachute descent in a lake in Finnish Lapland, 250 km away from the launch site. The radio contact was lost at 18:08 UTC, while the balloon was flying approximately at 3000 m Above Sea Level (ASL). The balloon path intersected five VOR stations operative volumes. Plots on the balloon flight path are presented in Fig. 6 and Fig. 7.

Fig. 5: BEXUS 22 flight train at launch, October 5th, 2016.

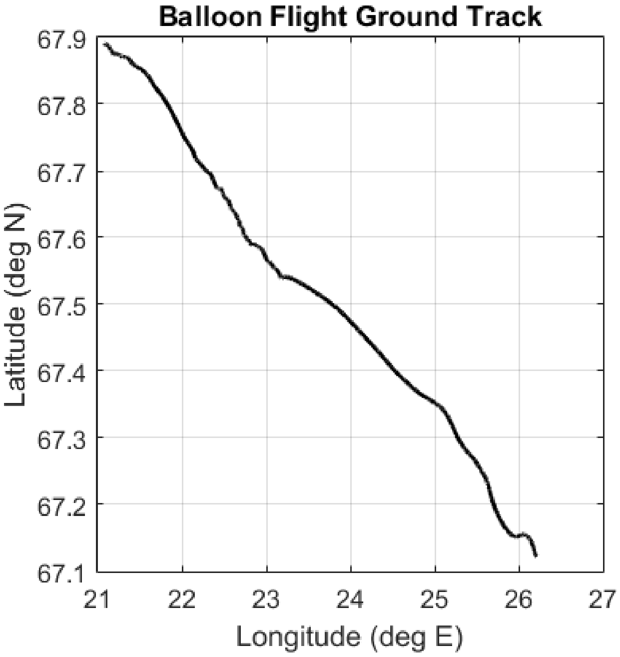

Fig. 6: BEXUS 22 balloon flight ground track.

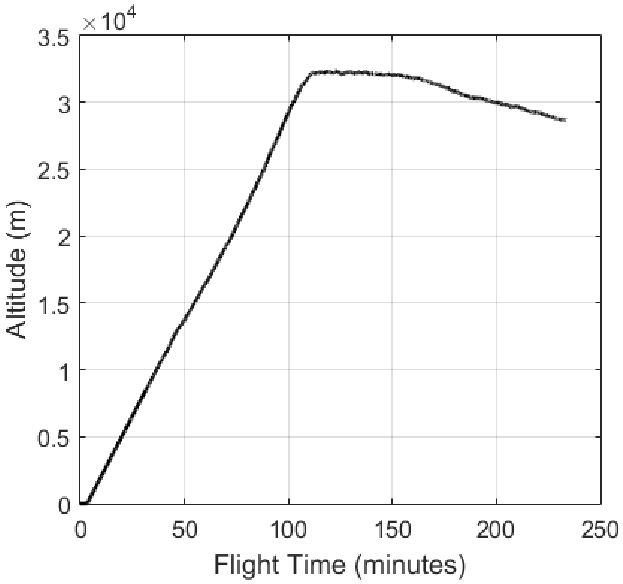

Fig. 7: BEXUS 22 balloon flight envelope (altitude vs time).

STRATONAV was able to acquire VOR radials, GPS fixes, and a set of housekeeping data such as internal temperature on different sides of the box, pressure, current delivered to each component and on the main power bus. All the components worked well and survived to the parachute hard landing in the Finnish taiga. All the data were both down linked to the experiment ground station through a S-band telemetry link and saved on the on-board memory units. The telemetry link remained fully functional for the whole flight, except the last 15 minutes of descending phase, in which the balloon was precipitating below the local horizon of the launch site.

3. Data collection and analysis processes

VOR data were collected by both the receivers (COTS and SDR) for the entirety of the BEXUS flight. Only data collected above 18 km of height (limit of the VOR SSV) were considered for the precision assessment. The data collected inside the SSV altitude limit were separated for both receivers.

The data analysis main process followed for both receivers is listed hereunder:

- Separation of samples collected above SSV limit altitude;
- Calculation or acquisition of radial measurement;
- Comparison with the correct radial, calculated from the balloon GPS data, and error calculation;

The samples both for the COTS receiver and the SDR receiver were separated on the base of the sample timestamp and on the GPS data. From the sample timestamp, GPS position and altitude were retrieved from the flight sensors data. If the sample was collected above 18 km of altitude, it was considered for the precision assessment. The following subparagraphs provide a more detailed description of i the data analysis processes carried out.

3.1. COTS Receiver radial acquisition

The VHF COTS VOR receiver was able to autonomously evaluate the radial by processing the received VOR signal in real time. The data processing flow for the radial acquisition from the COTS receiver is shown through the flow diagram in Fig. 8.

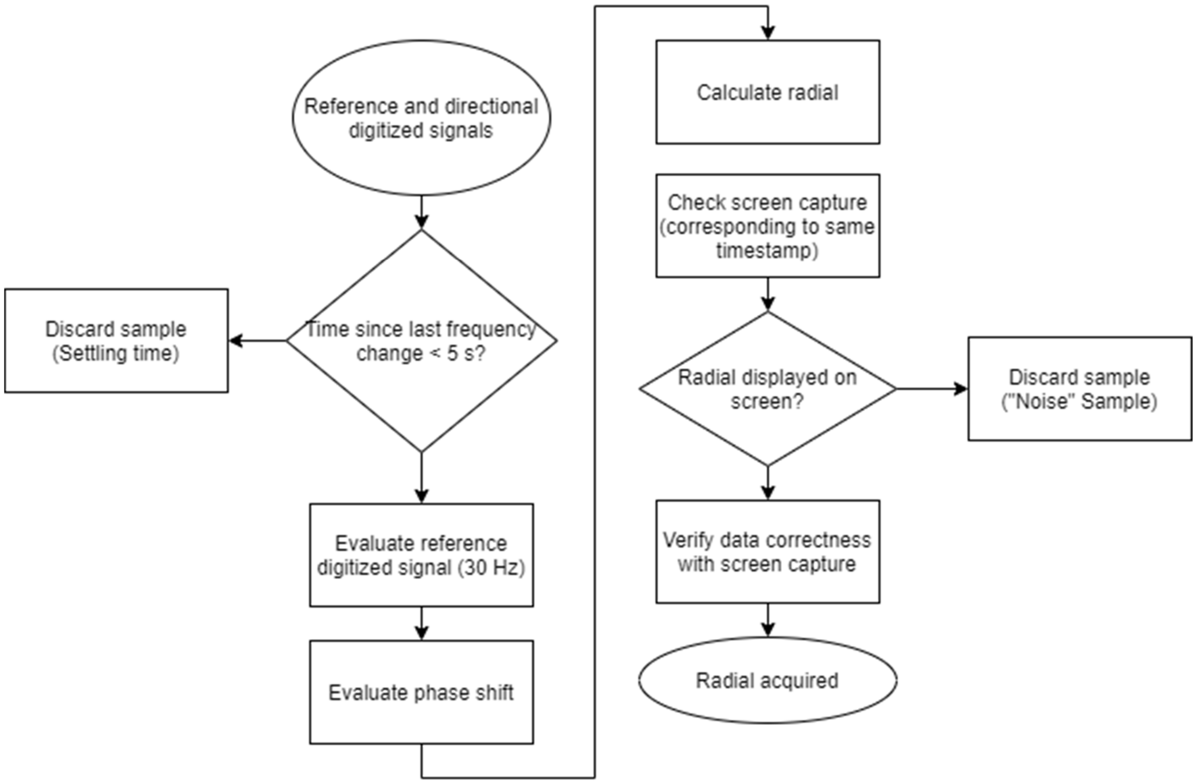

Fig. 8: COTS receiver radial acquisition flow diagram.

The VOR radials were recorded through an internal data tapping process: the raw directional and reference digitized signals were processed by OBC #1 in order to extract and save the radial. The phase shift measurement was performed by the OBC, that stored the calculated radial in the flight telemetry. Furthermore, a camera shot low-definition pictures to the COTS receiver screen, in order to verify the truthfulness of the calculated radials by comparison with the screen-projected data. For the whole duration of the balloon flight, radials were saved from the COTS receiver at 1 Hz. Moreover, the radio screen captures allowed to distinguish between the "data" samples (collected while a radial value was projected on the receiver screen, indicating a sufficient SNR of the received signal) and "noise" samples (typically affected by great radial oscillations in small time intervals, collected while no radials were shown on the COTS radio screen). Examples of “data” and “noise” samples are shown through the COTS radio screen captures in Fig. 9. Finally, radials acquired through the first 5 seconds from frequency tuning were eliminated in order to consider errors due to the COTS receiver measurement settling time (described in [22]) in the data analysis.

Fig. 9: COTS receiver screen captures taken during the STRATONAV flight, reporting “data” (a) and “noise (b) samples.

3.2. SDR radial calculation

During the experiment flight, the SDR only recorded signals in the VHF-NAV band and stored all the data inside a SSD. After the experiment recovery, several signal processing tools were realized to decode the collected signals and to extract the VOR radials. A scheme of the process is shown in **Fig. 10**. The demodulation of the SDR Data begins from the IQ (In-phase and Quadrature components) files recorded during the flight. These files contain the entire spectrum that was being received from the SDR and therefore multiple VOR stations at once. For each station, the signal is centered and then low-pass filtered in order to ignore the rest of the spectrum. The signal then undergoes typical VOR demodulation using FIR filters (Finite Impulse Response filters) replicating in software what happens inside the COTS receiver via hardware. The signal follows two paths, one for the reference signal, which is FM-demodulated, and one for the directional signal, which is AM-demodulated. The relative phase of the two remaining 30 Hz signals is in fact the radial. This process is repeated for all of the VOR stations inside the same recording file.

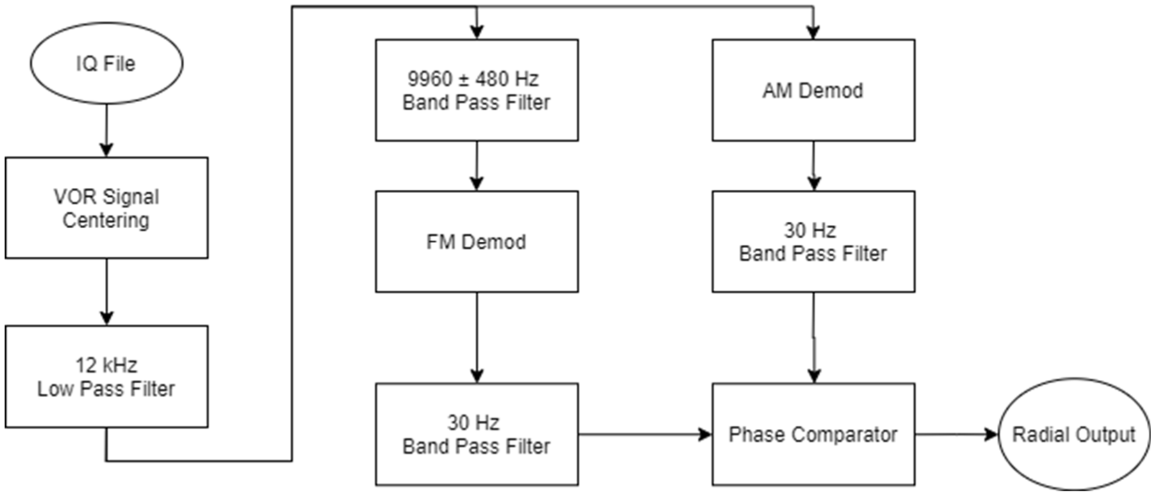

Fig. 10: Flow diagram of the SDR radial calculation process.

3.3. True radial calculation

In order to perform the precision calculation, the true radial was estimated on the base of the balloon GPS position and of the aeronautical charts. The VOR radial is the aircraft bearing angle with respect to the VOR ground station. The Magnetic North is taken as zero angle reference, the aeronautical charts ([6–8]) report the Magnetic Declination that needs to be added to the geographic bearing angle to retrieve the VOR radial measurement.

By considering each station geographical coordinates and every GPS fix of the balloon, the radial is calculated as follows.

$$VORrad = arctg\,\frac{\sin(\lambda_2-\lambda_1)\cdot\cos(\varphi_2)}{\sin(\varphi_1)\cdot\sin(\varphi_2)-\sin(\varphi_1)\cdot\cos(\varphi_2)\cdot\cos(\lambda_2-\lambda_1)}+MagDec$$

Where ϕ_1,λ_1 are the latitude and longitude of the VOR ground station, ϕ_2,λ_2 are the latitude and longitude of the balloon, MagDec is the magnetic declination retrieved from the aeronautical charts for the station.

4. Experiment results

The experiment collected VOR radials and recorded the VHF spectrum for the six hours of balloon flight. Several analyses have been performed on the collected data, in order to estimate the reliability of the VOR service above its SSV end while verifying the complete well-functioning of the on-board systems and the truthfulness of the acquired radials and signals. The data processing results on the VOR accuracy in stratosphere are described in the following sub-sections.

4.1 Altitude and Range distance performance maps

An evaluation of the radials while flying inside the VOR stations SSV was needed to verify the correct system behavior before calculating the reliability of the system in stratosphere, outside the SSV. To this purpose, a *performance map* has been produced for every VOR station by considering the altitude, the range distance from the tuned VOR station and the obtained precision of the collected data.

The COTS receiver overall behavior is well described in the performance maps for Kiruna and Natta stations, since the experiment has flown inside these stations SSVs for a large portion of the balloon flight, collecting a large amount of radials. The Kiruna and Natta COTS receiver maps are described in **Fig. 11** and ***Fig. 12***. To ease the graph visibility, radials collected within a sphere of radius 1 km have been averaged.

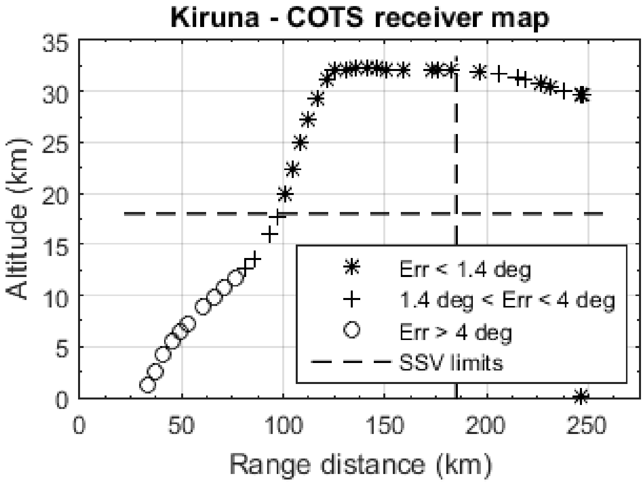

Fig. 11: Kiruna VOR COTS receiver performance map.

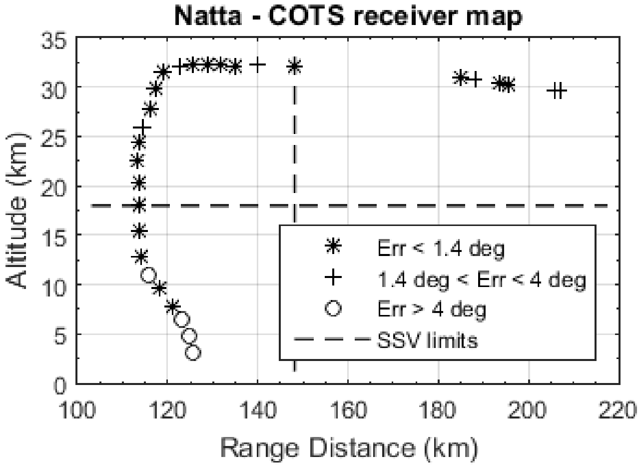

Fig. 12: Natta VOR station COTS receiver performance map.

In both COTS receiver plots, data collected below 8 km are characterized by low precision. The errors were probably caused by the VOR antenna branches folding encountered at low altitude and caused by the higher balloon climb rates at low altitude, consequently generating a high aerodynamic drag that forced the antenna branches to fold down. Moreover, the errors were caused by the high receivers inner temperature: since all the equipment was switched on six hours before lift-off, the internal receivers temperature was significantly higher than expected. The experiment operations were indeed expected to begin shortly before lift-off, without a warm-up time of hours between experiment switch-on and lift-off time. Further analyses on the receivers electric boards temperature effects on the radial measures are provided in the next sub-section.

The SDR data for Kiruna and Natta VOR stations are presented in Fig. 13 and Fig. 14.

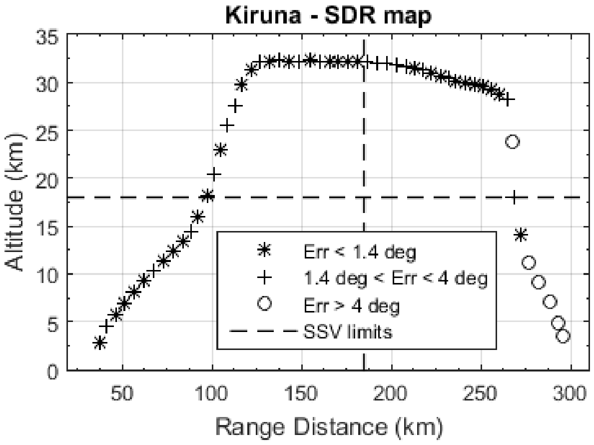

Fig. 13: Kiruna VOR station SDR receiver performance map.

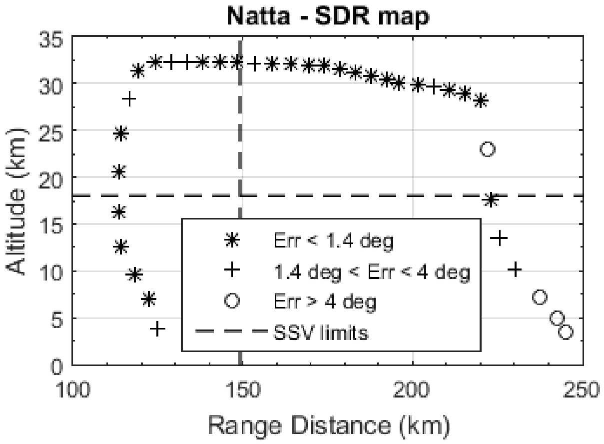

Fig. 14: Natta VOR station SDR receiver performance map.

With respect to the COTS data, the SDR radials appear to achieve a better precision, especially during the balloon ascending phase. Moreover, the data post-processing routines managed to evaluate the radials during all the balloon flight phases, including the descending phase, whose samples are absent for the COTS receiver.

In the COTS receiver Natta plot, many samples beyond the operative limit are missing, due to the OBC #1 automatic radio tuning feature that only considered frequencies within the stations range limit.

The obtained plots show that the standard precision of the VOR system is preserved beyond and above the SSV range and altitude limits, without any visible and precision degradation induced by the increased distance from the station. Indeed, in both stations and for both receivers there is a large presence of samples within 1.4

degrees of error without dependency on the flight altitude or range distance. In the final part of the floating phase, the already achieved mission objectives allowed the ground station operators to tune the COTS receiver to the farthest stations still in line of sight. Table 1 shows the results achieved during the farthest stations test.

Table 1: Achieved accuracy on farthest VOR stations.

Station ID	**Station name**	**SSV range limit (km)**	**Average distance (km)**	**COTS mean error (degrees)**	**SDR mean error (degrees)**
ATA	Alta	111.12	333.3	2.087	1.060
BNA	Banak	111.12	329.1	1.031	0.760
SDA	Seida	111.12	353.2	0.509	1.850
SLU	Lulea	111.12	251.5	1.380	1.210

4.2 Accuracy rates and errors investigation

The collected radials error distribution is described in Table 2 with respect to the mean error and the standard deviation (only data collected above the SSV estimated end, above 18 km of altitude are considered). The fields in Table 2 highlighted in green present a 1σ deviation below 4 degrees of error, as per mission objective. Data highlighted in orange present a low mean error (within 4 degrees), but a high standard deviation causing the ±1σ interval to exceed the 4 degrees range. As reported before, the SDR collected data from a larger number of stations due to the architecture of the data collecting processes. Indeed, while the COTS receiver was able to collect radials from one station at a time, the SDR continuously recorded the whole VHF NAV band with all the VOR signals.

Table 2: Accuracy of the acquired VOR data.

Station name (ID)	**Average distance (km)**	**COTS receiver**		**SDR**	
		Mean error (deg)	**Standard deviation (deg)**	**Mean error (deg)**	**Standard deviation (deg)**
Rovani	119	2.16	0.98	0.76	0.57
Natta	163	0.26	6.50	1.75	-0.12
Kiruna	180	1.09	0.62	1.84	0.77
Lulea	240	1.38	0.90	1.53	1.21
Oulu	282	NA	NA	94.44	-78.38
Alta	296	2.09	0.34	1.31	1.06
Banak	304	0.35	4.42	10.17	-1.85
Bardufoss	310	NA	NA	25.09	6.49
Tromso	341	NA	NA	39.52	23.02
Evenes	345	NA	NA	2.49	-1.88
Kirkenes	345	NA	NA	1.87	1.22
Skelleftea	349	NA	NA	73.13	34.24
Seida	353	0.51	9.22	1.74	-0.76
Storuman	410	NA	NA	3.24	9.31
Skagen	413	NA	NA	55.63	54.59
Vardo	426	NA	NA	90.31	-48.32
Vardefjell	520	NA	NA	49.74	130.48
Bronnoy	585	NA	NA	45.39	120.29

The closest stations (the ones received by the COTS receiver) present results and accuracy rates within the mission objectives error limits, confirming that the VOR can be used as reliable radio navigation system for stratospheric platforms.

While the SDR data maintains similar trends for the radial mean error and standard deviation, the COTS receiver data reveals the opposite behavior of the mean error and the standard deviation. Indeed, when a higher mean error is observed, it is often coupled with a low standard deviation. Vice versa, when the VOR data from one station is characterized by a low mean error, it often presents a high standard deviation. Hence, the two main encountered error typologies are:

- a random error, characterized by low mean error and high standard deviation values, mainly caused by noise and phase shift oscillations;
- a systematic error, characterized by high mean error and low standard deviation values, whose causes were investigated after the flight.

A systematic error also affected the SDR recording processes, consisting in a recording center frequency shift. The error cause has been identified as a frequency shift of both the COTS receiver and SDR local oscillators due to high temperatures. Indeed, even if the internal temperature of the experiment box was lower than expected (below 15 °C for the whole flight), both the receivers were operating for six hours before lift-off in order to perform several flight compatibility tests. The experiment remained switched on between the tests and lift-off in order to keep the temperatures as high as possible, even while being exposed to a nearly 0 °C temperature. Moreover, a low temperature could not cause a frequency shift in the COTS receiver, due to its internal architecture: several thermistors record the temperature and, if too low, multiple heaters (resistors) are switched on in order to reach a proper oscillator temperature.

The temperature influence on the radial error is highlighted in **Fig. 15**.

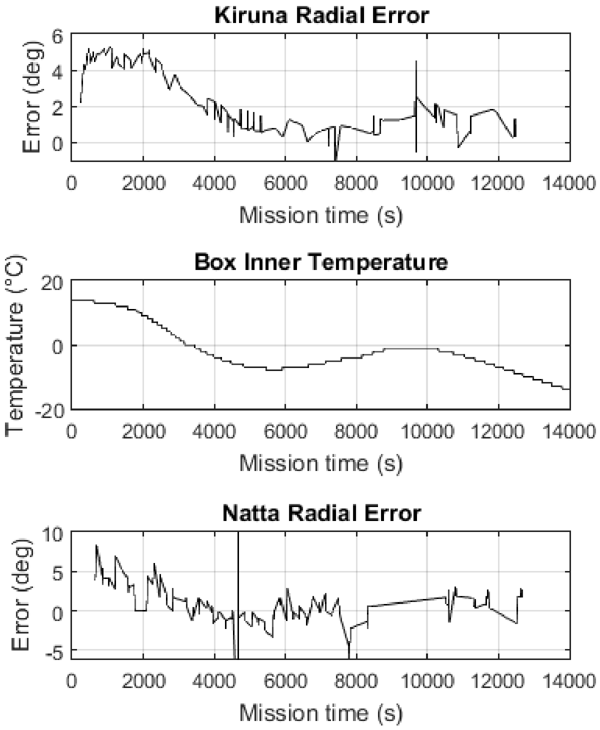

Fig. 15: Comparison between the error trends on Kiruna and Natta acquired radials and the experiment box temperature over flight time.

The error on both stations' radials is perfectly consistent to the inside box temperature trend. The plots referring to Kiruna and Natta stations as data from those stations are available throughout all the flight phases.

A post-flight test was performed by heating the inner PCB side of the COTS receiver back-up model while measuring the screen-projected radial. The receiver was connected on a large antenna close to Rome Ciampino airport VOR, at approximately 6 km of air distance from the station, in order to maximise the received power. The temperature profile vs the radial shifts are reported in Fig. 16.

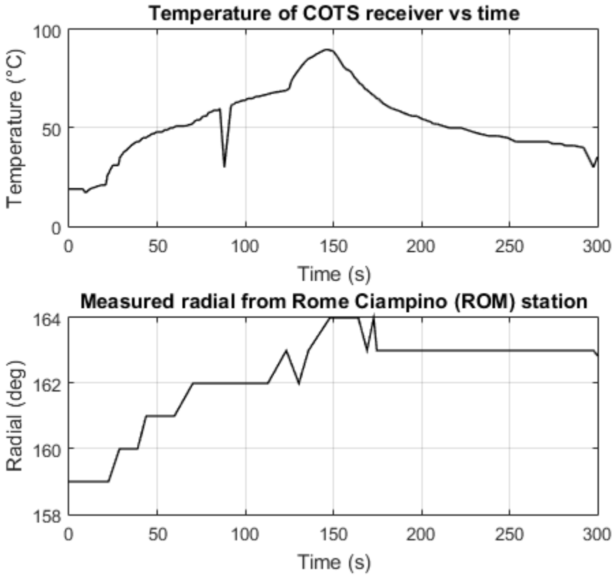

Fig. 16: Comparison between the trends of COTS receiver error on Rome Ciampino (ROM) station and the COTS receiver measured temperature, as measured during the conducted post-flight test in December 2016.

Before the test, the radial measurement was stable. During test, the radial appeared increasing of 5 degrees with a temperature shift of approximately 50°C. The test confirmed that the radial instabilities related to the COTS receiver were caused by temperature shifts on the COTS receiver electronics, although not impeding to achieve a good experiment result in the VOR precision investigation in stratospheric flight.

4.3 Overall accuracy rates of COTS receiver

The accuracy of the radials successfully collected by the COTS receivers were analyzed to estimate the percentage of samples presenting an accuracy within the current VOR standard or within the previous system standard (defined as mission objective). This analysis only involves the COTS receiver, the only device able to autonomously discriminate between consistent samples and noisy samples. If conducting the same analysis on the SDR data, a lot of collected data would return high errors because of the high noise due to low elevation and great distance from the station. Table 2 illustrates how this receiver has collected samples with high error from stations that were very low on the horizon. Table 3 presents the accuracy rates collected by the COTS receiver. The results are presented both when considering the “blank”, noisy samples that do not provide a radial estimation on the receiver screen, and when discarding those samples from the total amount.

Table 3: COTS receiver achieved accuracy for all the acquired samples.

	“DATA” AND “NOISE” SAMPLES			“DATA” SAMPLES ONLY		
STATION	**Samples**	**< 1.4 deg**	**< 4 deg**	**Samples**	**< 1.4 deg**	**< 4 deg**
Kiruna	940	70.95%	98.29%	926	72.03%	99.78%
Natta	884	61.76%	97.51%	884	61.76%	97.51%
Rovani	433	7.85%	99.77%	433	7.85%	99.77%
Lulea	178	48.88%	100%	178	48.88%	100%
Alta	65	0%	100%	65	0%	100%
Banak	301	59.14%	95.70%	186	64.46%	99.46%
Seida	97	79.38%	79.38%	92	83.70%	83.70%
TOTAL	**2315**	**52.74%**	**88.38%**	**2066**	**59.10%**	**99.03%**

The results confirmed that the mission objective was achieved, with the majority of samples (both when considering and discarding the noisy samples) below 1.4 degrees of error, as per current standard, and the 99% of samples compliant to the 4 degrees previous accuracy standard.

6. Applicability of the conducted research

STRATONAV demonstrated the VOR accuracy in stratosphere and the applicability of this system to stratospheric navigation systems. VOR can be applied, as stated in the introduction, as system for reliability improvement of all kinds of stratospheric missions, e.g. long-term stratospheric platform quasi-satellite tasks, disaster relief missions, meteorological sounding with simple navigation units, even future manned stratospheric or trans-atmospheric vehicles.

There is a great interest into the establishment of a higher number of stratospheric platform missions [23–26], to be equipped with low power electric propulsion systems [17] able to counteract the low winds of the stratopause altitude range [15,16]. These missions are often referred with the names of “High Altitude Platform Stations” (HAPS),to provide imaging or telecommunication links with a much lower development and installation costs than conventional satellite missions [11]. If considering HAPS for disaster relief, launches of stratospheric platforms require less planning and scheduling with respect to satellite and they can assure a permanent time on target, achievable on space systems just by constellations. The perspective of “on condition” relief radio-links and imaging payloads is extremely interesting for these types of systems [27–29]. VOR can be applied to these vehicles jointly with navigation systems of other nature (GNSS, INS, often coupled as primary navigation systems for various typologies of aircraft [30–32]) to assure the needed rates of reliability.

While flying in an area densely interested by intersecting VOR standard service volumes, it will be possible to use the VOR-based navigation system for automatic ground track reconstruction by intersecting two or more collected radials in a single instant and by applying relatively simple geodesy algorithms or Geographic Information System (GIS) models. Although it was not the main mission objective, an analysis on the usefulness of the STRATONAV data from ground track reconstruction is being carried out along with the design of miniaturized, low -cost, low-complexity and low-power systems that can serve as back-up positioning system for stratospheric platforms and experiments.

Moreover, VOR can even be used as a coarse attitude determination system. While radio-direction finding techniques can track the relative attitude of the vehicle with respect to the signal source direction, the VOR stations known position and radial can be interfaced to the acquired direction data to collect the absolute yaw angle of the vehicle. This can be exploited for pointing antennas or cameras towards a specific target. This would make the VOR exploitable as stratospheric positioning and attitude determination system [33].

7. Conclusions

The VOR aircraft navigation system can be exploited by stratospheric platforms for back-up and/or low cost navigation systems. Although guaranteeing service and correct functionality until approximately 18 km of height, link budgets calculations show that a enough power density should be reached well above and beyond the service volume limits.

The STRATONAV Experiment developed in the framework of the REXUS/BEXUS Programme, was aimed at testing the VOR accuracy rates on a stratospheric balloon. The experiment, equipped with a commercial COTS VOR receiver and an SDR receiver, flew on-board the BEXUS 22 stratospheric balloon.

The experiment succeeded in collecting a great amount of data both inside and outside the VOR service volume. Both the receivers recorded accuracy rates widely sufficient to consider the service functional and perfectly operational up to the balloon floating altitude. While the "performance maps", i.e. the plots of reached precision vs range and altitude with respect to the station, record that the accuracy rates remain constant when crossing the service volume boundaries, the experiment acquired data with a precision in line with the previous VOR accuracy standard normative from 4 stations (COTS receiver) and 7 stations (SDR). The 4 closest stations to the balloon ground path were serving the balloon with precise data, with a mean error spanning between 0.26 and 2.16 degrees and a standard deviation in the range between 0.12 and 1.21 degrees. The errors with higher impact on the collected data are related both to noise in the RF station, creating fluctuations in the data and impacting on the standard deviation of the collected radials, and from the receivers oscillator temperatures. This last one, is highly recognizable if comparing the trends of the experiment box temperature plots and the average error on the receivers. The effect of the temperature error is more visible on the mean error, with less impact on the standard deviation (systematic error). Anyway, even if affected by this error, the experiment collected precise and reliable data. An analysis on the samples percentage with error below the maximum allowed error rate of the current and previous VOR standard showed that 99% of the "data" (i.e. samples achieving a consistent radial determination on the COTS receiver) radials collected in stratosphere were presenting an error below 4 degrees.

The results of STRATONAV demonstrate the VOR applicability for stratospheric flights. Many future High Altitude Platform Stations could benefit from a navigation systems reliability improvement offered by this system. Furthermore, low-cost weather sounding balloon missions could benefit from a VOR-based navigation unit by implementing commercial SDR receivers and low-power microcontrollers.

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