ANALYSIS ON THE FEASABILITY OF AIRBORNE GNSS-R RECEIVERS FOR WEATHER NOWCASTING AND TARGET DETECTION

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ABSTRACT

Weather forecast relies to a large extent on data acquired by satellite. LEO polar satellites provide global coverage, but poor spatial resolution. GEO satellites provide a better coverage and revisit time, at expenses of poorer spatial resolution. LEO constellations of small satellites offer the promise of global coverage with good spatial resolution and revisit time. However, hosted payloads on aircrafts offer the potential of very high resolution and very low revisit time for regional applications.

In this work, the idea of equipping commercial airliners with low-cost Global Navigation Satellite System - Reflectometer (GNSS-R) receivers is explored, with emphasis on real-world data and the implications the expected scientific yield would offer.

Index Terms— GNSS-R, airplanes, weather nowcasting, Earth observation

1. INTRODUCTION

GNSS-R is a growing technology. It has been proven from ground based equipment, airborne instruments, and also satellites.

Ground-based instruments have been broadly used to validate models, technologies, and also to provide periodic measurements over the same area. However, these types of sensors lack the versatility of mobile ones, such as the capability of taking measurements from different areas.

This technology has been proven to work in mobile environments through three space-based missions: UK-DMC, TDS-1, and CYGNSS. The former was only a proof of concept mission that demonstrated the capabilities and performance of GNSS-R from space, whereas TDS-1 and CYGNSS have provided a great amount of GNSS-R data that has been successfully used for sea state retrieval [1], sea ice detection [2], soil moisture [3], and even target detection (i.e. boats in the middle of the ocean), among others.

Despite GNSS-R has already been deployed in spaceborne systems, airborne based GNSS-R can provide the same measurements and applications as the spaceborne case, but with an improved spatial resolution in the case of specular reflections [4] and much better revisit time over the flight routes. In the case of specular reflection, the spatial resolution of the sensor is significantly improved as the reflection is determined by the size of the first Fresnel zone, which depends on the instrument altitude as $l_{Fr} = \sqrt{\lambda h}$ [4], which is in the order of 45 meters for an airplane flying at a 10 km height, whereas for a spacecraft orbiting at a height of 500 km, it would be in the order of 300 meters.

Fig. 1: Commercial Airplanes location the 10-01-2020 at 10:00 UTC

This improvement, coupled with the relaxation of power, cost, and space budgets on board airplanes as compared to spacecrafts, and the increased revisit time for remote places due to the sheer number of commercial airplanes in-flight at a given time, prompts for a feasibility study to explore a possible implementation.

2. COMMERCIAL AIRPLANE TRAFFIC AND POTENTIAL APPLICATIONS

The possibility to include simple and low-cost GNSS-R receivers in commercial airplanes, such as the Airbus A320 or the Boeing 737-800 (the most common ones), yields a huge amount of data with very low revisit times over the flight routes. There are approximately 25.000 planes in the world, from which 10-000-15.000 are flying at any given

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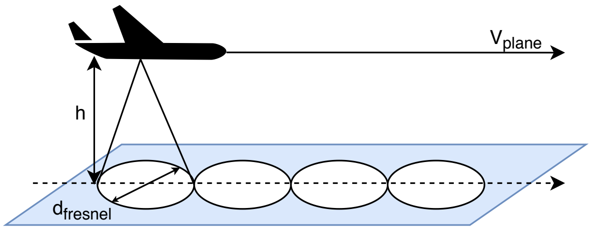

Fig. 2: Diagram of the relationship between the first Fresnel zone's diameter and the plane's path

time. The amount of commercial airliners that could be fitted with GNSS-R equipment is estimated to be 5.000 planes.

As shown in Fig. 1, most commercial airplanes follow routes over land. This fact can be used for soil moisture measurements based on GNSS-R data with very short revisit times. Such a strategy would also allow for the use of time series-based differential data which would remove surface roughness and vegetation effects [5].

In addition to soil moisture measurements, as commercial aircrafts are also covering transoceanic flights, they can implement wind speed measurements to the ones obtained by the NASA CYGNSS constellation.

3. FEASIBILITY DISCUSSION

The feasibility of a mass deployment of GNSS-R instruments is mainly based on the acquisition of the data, and its recovery

3.1. Data acquisition

GNSS-R physical measurements are mostly related to the delay difference between the direct and the reflected signal (altimetry), the peak power difference between the direct and the reflected signal (scatterometry), or the shape of the Delay-Doppler Map (DDM) [6]. For all three cases, an IQ data recorder or a DDM imager is required, which translates to an instrument that computes DDMs or waveforms of the GNSS satellites in view.

In case of using a simple IQ recorder such as a Software Defined Radio (SDR), the amount of data generated depends on the type of GNSS signals the requirements in terms of sampling rate are very different. For instance a GPS L1CA signal is sampled with 2 MS/s, but a GPS L5 signal requires up to 20 MS/s, a factor of 10. However, a DDM imager that only stores several samples around the peak is able to reduce the amount of generated data from 20 MS/s (in the L5 case) to 1000 samples once every 50 milliseconds (i.e. incoherent integration time) per satellite in view (i.e. 10 satellites).

The rate of acquisition for the system depends on the height and speed of the plane. The height h is proportional to the square of the diameter of the first Fresnel zone $d_{Fresnel}$, which corresponds with the diameter of the footprint where the specular reflection is dominant:

$$d_{Fresnel} = \sqrt{h \cdot \lambda} \tag{1}$$

where λ is the wavelength of the signal.

In order for the footprints to not overlap and reduce the amount of data recovered, it is necessary to limit the rate at which DDMs are calculated. For a plane travelling at a speed v_{plane}, the number of DDMs to be calculated per second $\frac{N_{DDM}}{s}$ should be approximately

$$\frac{N_{DDM}}{s} = \frac{v_{plane}}{d_{Fresnel}} \tag{2}$$

To obtain an approximation of the amount of data to be generated by each plane, the following assumptions will be used:

- Height of the plane: 10 km
- Frequency: 1.575 GHz
- Speed of the plane: 230 m/s
- Number of samples per waveform: 100 samples
- Number of bits per sample: 16 bits / sample
- Number of satellites to track: 10 satellites
- Size of the metadata header: 32 bits

By using the aforementioned values, we can substitute in Eq. 1 and 2 to obtain:

$$d_{Fresnel} = \sqrt{10e3 \cdot \frac{3e8}{1.575e6}} \sim 50m \tag{3}$$

$$\frac{N_{DDM}}{s} = \frac{230}{50} \sim 5 \frac{N_{DDM}}{s} \tag{4}$$

This would result in

$$R_{plane} = 100sps \cdot (16+32) \frac{b}{sps} \cdot 10\text{sats} \cdot 5 \frac{N_{DDM}}{s} = 240Kbps, \tag{5}$$

which in turn, for an average of 5000 commercial airplanes in-flight at a given time would result in

$$R_{total} = 240e3 \cdot 5000 = 1.2Gbps \tag{6}$$

The total amount of captured data for transatlantic flights would be around 1.2 GB ($\sim$ 11 hour flights), and 216 MB for intereuropean flights ($\sim$ 2 hour flights), as an example. This amount of data can be easily handled by modern systems, so recovering it becomes the main hindrance to overcome.

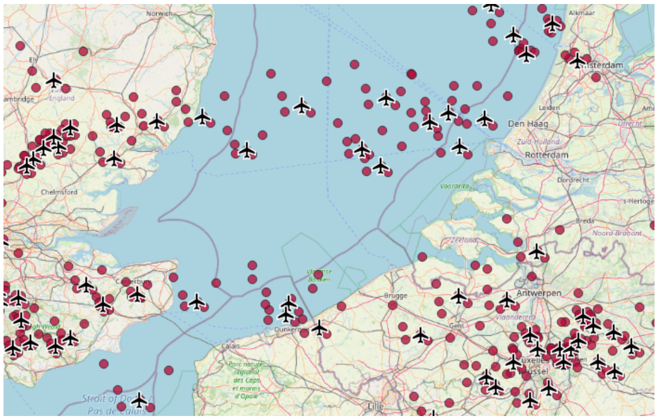

Fig. 3: Spread of the specular points under different planes, showing the differences for several heights.

3.2. Data recovery

There are mainly two options for data recovery: in-flight or after landing. The in-flight downlink for the generated data rate (Eq. 6) would have to be performed via satellite communication services such as Starlink or OneWeb. Recent studies have found the throughput of these Low Earth Orbit (LEO) satellite constellations to be sufficient for this endeavor, with a minimum around 1.1 Tbps and a maximum of 20 Tbps [7]. Successfully implementing this option, with the corresponding real-time processing and publishing, would result in weather nowcasting for even remote regions of the Earth, as long as airliners flew close to them. On the opposite side, if the data were to be recovered after landing, the total amount of captured data would be easily downloadable through WiFi connections at the airport during airplane servicing. The main drawback of this approach would be that the data access time could be as high as 14 hours for the longest flights. A more efficient implementation would be to define areas where weather nowcasting can be supplied by other less resource-expensive means, and only use in-flight downlink via satellite communication for areas in need of this technology.

In both cases, the end result is vastly superior to current technologies, and thus a viable option to obtain weather nowcasting or forecasting at reasonable delay.

4. COVERAGE SIMULATION

Real plane positions with an accuracy of 10 seconds have been stored [8] during the course of a whole year to simulate the scientific yield of equipping each plane with a GNSS-R receiver. Once all plane positions were obtained with an interval of 10 seconds, the GPS satellites' positions also needed to be calculated. Using data downloaded from the Crustal Dynamics Data Information System (CDDIS) [9] from NASA, the ephemeris and almanac of a certain GPS Satellite at a specified time can be reconstructed, along with their position.

Using the same procedure found in [10], the specular point of the reflection of the GPS signal on the Earth's surface before being captured by the tentative down-looking antenna of each plane is obtained. Thus, for each plane in the world and for each 10-second window in several months of data, 5-12 specular points (belonging to the different GPS satellites in view) were calculated with a precision under 10 meters, as seen in Fig. 3.

Due to the amount of data generated (ranging in the trillions of points), aggregation of 3 hours of data in 1 km hexagonal grids was performed. As a case study, the authors focused on Spain as a proof of concept of both coverage and calibration of sensors. The main airports in Spain are in Madrid (Fig. 4a center), Barcelona (top right), and Palma (right). Due to their geographical position, and the fact that most planes travel westward (to America) or northward (rest of Europe), it can be seen that the upper part of Spain has a better coverage than the southern. Even then, as it can be seen in Fig. 4b, up to 86% of Spain is covered by a GNSS reflection in a single day, with most of the measurements concentrated between 9 AM and 3 PM.

The calculated average revisit time over Spain was calculated as the average revisit time per hexagon over the 3-hour period, averaged over the entire day, which resulted in 1.214 reflections per 3-hour slot, with a standard deviation of 1.821. In order to calibrate the sensors, the REMEDHUS network of soil moisture sensors, near the city of Salamanca was chosen as an area of study. The entire area was visited at least once a day, with peaks of up to 100 times in some zones.

5. CONCLUSION

The results obtained over Spain clearly show the potential of this technique to perform weather nowcasting over land. Installing cheap GNSS-R instruments in commercial airliners or small planes would provide excellent coverage over selected areas. Due to the nature of the obtained data, studies for specific airplane companies (and their projected coverage) or for specific areas (and the best suited companies or airplanes to cover them) could be performed. Data processing for the rest of the world and other areas of interest is still ongoing.

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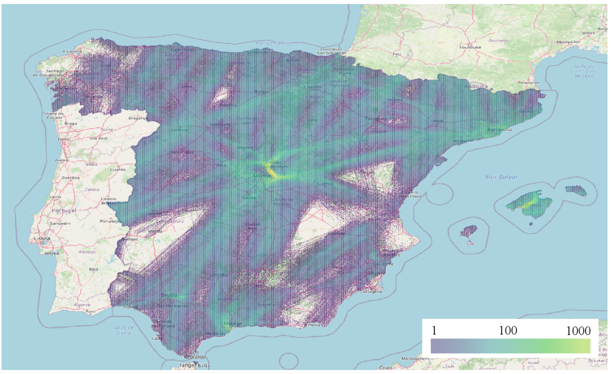
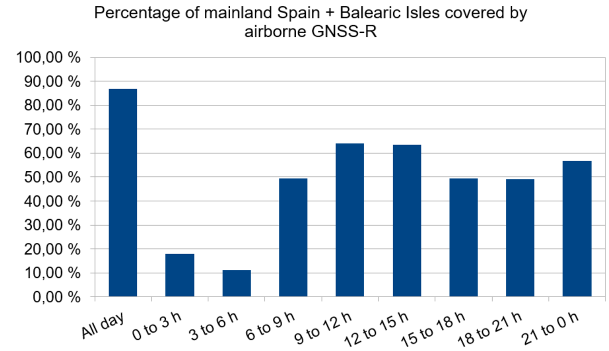


(a) Specular point density in mainland Spain for a single day, using a 1km square grid.



(b) Percentage of Spain where GNSS-R measurements were obtained in a single day, averaged over a week.

Fig. 4: Coverage study over mainland Spain plus the Balearic Isles

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