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The Radio Occultation System (ROC) for Stratospheric Balloons

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Abstract

Climate models show that the sea level pressure response to a doubling of CO2 in the atmosphere is a decrease in pressure centered over Antartica and an increase in pressure in the mid-latitudes, which indicates a trend towards high index polarity of the Southern Hemisphere annular mode (SAM). This results in an increase in the strength of the circumpolar westerlies and intensification of the Antarctic polar vortex. The increase in westerlies, in turn, has a strong affect on sea ice distribution and regional surface temperature trends, in particular an increase in surface temperature over the Antarctic peninsula and Weddell Sea that affect the state of the Antarctic peninsula ice shelves. However, this intensification of the westerlies and the Southern Annular Mode is also consistent with the response from changes in stratospheric ozone, because of its affect on the radiation balance in the high latitude southern hemisphere, therefore these two forcings are difficult to distinguish. This challenge is complicated by the fact that sea level pressure trends from reanalyses have been shown to have biases in the Antarctic because of the sparsity of surface and upper air observations in this harsh environment.

GPS radio occultation profiles that will become available from stratospheric balloons will increase significantly the distribution of atmospheric profiles for improving the quality of global and regional reanalyses. These observations will help characterize the upper troposphere / lower stratosphere temperature that is critical for understanding the effect of ozone depletion on the Southern Annular

Mode; they will increase the sampling over the polar oceans to improve modeling of surface fluxes and coupling with ocean models, and in general they will increase the quality of reanalyses and the dataset available for validating climate models in the southern hemisphere. The observations will also specifically provide data for understanding the momentum flux carried by gravity waves into the stratosphere and the global transport of ozone. These observations provide strong constraints on the parameterization schemes that are used in general circulation models to mimic the dynamical effect of the unresolved gravity waves.

The GPS balloon occultation observations took place during the instrumented flights of stratospheric balloons over the Antarctic in Autumn 2010 (austral spring). The flights were designed for studying ozone, gravity waves and atmospheric circulation using in-situ sensors and dropsondes. The high accuracy dual frequency GPS receivers recorded 56 days of data during flight PSC18 and 41 days of data were recorded by flight PSC19. In a typical six hour period, of the 10 occultations that occurred, data was retrieved for the best three occultations, as planned given the limited bandwidth of the Iridium transfer link. PSC18 recorded data from two antennas on 12-13 October in order to determine the balloon dynamics in terms of rotation and oscillation. A higher rate data set at 5 second sampling was recorded on flight PSC19 on 24 October as the balloon passed over the Antarctic peninsula to investigate gravity wave motion of the balloon over a wider range of frequencies. Preliminary processing of one flight day to retrieve the precise position of the platform indicates very high quality carrier phase observations that are encouraging for the prospects of the occultation retrievals.

Introduction

Climate models show that the sea level pressure response to a doubling of CO_2 in the atmosphere is a decrease in pressure centered over Antartica and an increase in pressure in the midlatitudes related to changes in mid-tropospheric temperature gradients (Cubasch et al., 2001). This trend in the Southern Annular Mode (SAM) results in the intensification of the Antarctic polar vortex and an increase in the strength of the circumpolar westerlies. The increase in westerlies, in turn, has a strong affect on sea ice distribution and regional surface temperature trends, because of the eastward displacement of the south Atlantic storm center cutting off the atmospheric branch of the Weddel Gyre. As a result, models show that surface temperatures in the Weddel Sea and over the Antarctic peninsula have risen by as much as 8^{o}C, affecting the state of the Antarctic Peninsula ice shelves, and cooled up to 5^{o}C in East Antarctica (van den Broeke and van Lipzig, 2003). Regional air-sea-ice feedbacks such as this can amplify greenhouse warming and lead to rapid regional warming (Vaughan et al., 2003).

However, (Thompson and Solomon, 2002) have shown that stronger westerly flow in the Antarctic polar vortex associated with a change in the SAM is correlated with trends in total column ozone. Lower stratospheric temperatures have cooled by about 10 ^{o}C, and the seasonal polar vortex breakdown has been delayed from early November to late December. Modeling and analysis of high resolution vertical structure of the atmosphere (Gillett and Thompson, 2003; Shindell and Schmidt, 2004) has led to the conclusion that both factors – Antarctic ozone depletion and greenhouse gas increases – have a positive effect on the SAM and lead to increases in surface temperature that rise more rapidly than elsewhere in the southern hemisphere.

The challenge in distinguishing climate change forced by increased greenhouse gases and ozone depletion is complicated by the fact that reanalyses have been shown to have biases in the Antarctic (Hines et al., 2000), which affects the interpretation of changes in the Southern Annular Mode (Marshall, 2003). Analysis fields from the Polar MM5 simulations in Antarctica also have deficiencies in pressure fields due to gravity wave parameterizations (Guo et al., 2003). Accurate reanalysis fields are critical for global and regional climate modeling, but their improvement in the southern latitudes has historically been plagued with sparse surface and upper air observations. The Antarctic First Regional Observation Study of the Troposphere (FROST) (Bromwich et al., 1999) in 1996-1999 uncovered deficiencies in the NCEP-NCAR and ECMWF reanalyses and led to major improvements in the southern hemisphere. We expect the intense observations of the International Polar Year (IPY) Concordiasi campaigns, including GPS balloon occultation profiles as well as increased use of polar satellite sounding data, will contribute to similar improvements in reanalysis quality.

The proof-of-concept stratospheric balloon GPS radio occultation observations that were collected during Concordiasi 2010 will be used for validating global model assimilation methods that are under development for assimilating satellite data in the southern hemisphere. New high-resolution polar orbiting sounders such as the Infrared Atmospheric Sounding Interferometer (IASI) and the Atmospheric Infrared Sounder (AIRS), and the Advanced Microwave Sounding Unit (AMSU)-A and -B are providing a large quantity of global data. However the quality of the data and the assimilation techniques poleward of 65^o lat in the Antarctic environment have not yet been fully tested because of difficulties over snow and ice, and because cloudy conditions can affect 75-90% of the data. Stratospheric balloon driftsonde profiles that were also collected during Concordiasi from 13 of the balloons, combined with the radio occultation profiles from two balloons will be the primary datasets used to test data assimilation in the Antarctic. The improved model reanalyses using data from IR and microwave sensors will have an impact long beyond the duration of the campaign, and will be used by scientists for evaluating climate change. The resulting improvement in the representation of polar dynamics will be useful for coupled chemistry models that simulate the distribution of ozone and its evolution during the spring breakup of the polar vortex.

This proof-of-concept experiment will also assess the potential for developing an operational radio occultation component to the driftsonde NSF observation facility. It would significantly expand the utility of the driftsonde platform by enabling continuous observations after the finite number of dropsondes had been expended, and also by providing collocated measurements that are representative of a larger horizontal sample of the atmosphere.

Antarctic field campaign - Concordiasi 2010

This unique opportunity for GPS occultation observations is possible due to coordinated international research efforts for a stratospheric balloon campaign as part of the International Polar Year in Antarctica (Rabier et al., 2010). The stratospheric balloon payloads are divided into three types, based on science objectives, and constrained by weight limitations. The first part of the campaign from 8 September through 15 September launched 4 balloons flights equipped with microphysics and ozone sensors. These flights support the Physics, Chemistry and Stratospheric Dynamics (PSC) mission of the IPY research. From 23 September through 26 October, the 13 balloons containing driftsonde packages were launched in support of the Meteorology and Stratospheric Dynamics (MSD) mission.

Figure 1 Deployment of a stratospheric balloon during CONCORDIASI, 2010 (Photo: Philippe Cocquerez).

Two balloons with radio occultation packages (ROC) and ozone sensors (PSC flights) were launched immediately following two of the MSD driftsonde flights, on 29 September and 9 October, to maximize the proximity of dropsonde and radio occultation profiles for intercomparison during the beginning of the flights. At the end of the ROC flights in December 2010, 56 days of data had been recorded by flight PSC18 and 41 days of data had been recorded by flight PSC19. In a typical six hour period, of the 10 occultations that occurred, data was retrieved for the best three occultations. This compromise was chosen in order to remain within the bandwidth of the Iridium data link, for the proof-of-concept experiment. We are currently processing this data set. In addition, the ROC system on PSC18 recorded data from two antennas on 12-13 October in order to determine the balloon dynamics in terms of rotation and oscillation. A higher rate data set at 5 second sampling was recorded on flight PSC19 on 24 October as the balloon passed over the Antarctic peninsula to investigate gravity wave motion of the balloon over a wider range of frequencies. Preliminary processing of one flight day to retrieve the precise position of the platform indicates very high quality carrier phase observations that are encouraging for the prospects of the occultation retrievals.

Flight - Receiver	PSC18 Receiver 1	PSC18 Receiver 2	PSC19 Receiver 1
Start date	2010-09-29	2010-09-29	2010-10-10
End date	2010-11-29	2010-11-29	2010-11-22
Number of days recorded	54 days	1 day: 2010-10-13	42 days
Number of complete days	22 days	0	19 days
Median hours for other days	16.3 hours	12 hours	16.0 hours
Number of occultations per 24 hr	13 rising 13 setting	-	13 rising 13 setting

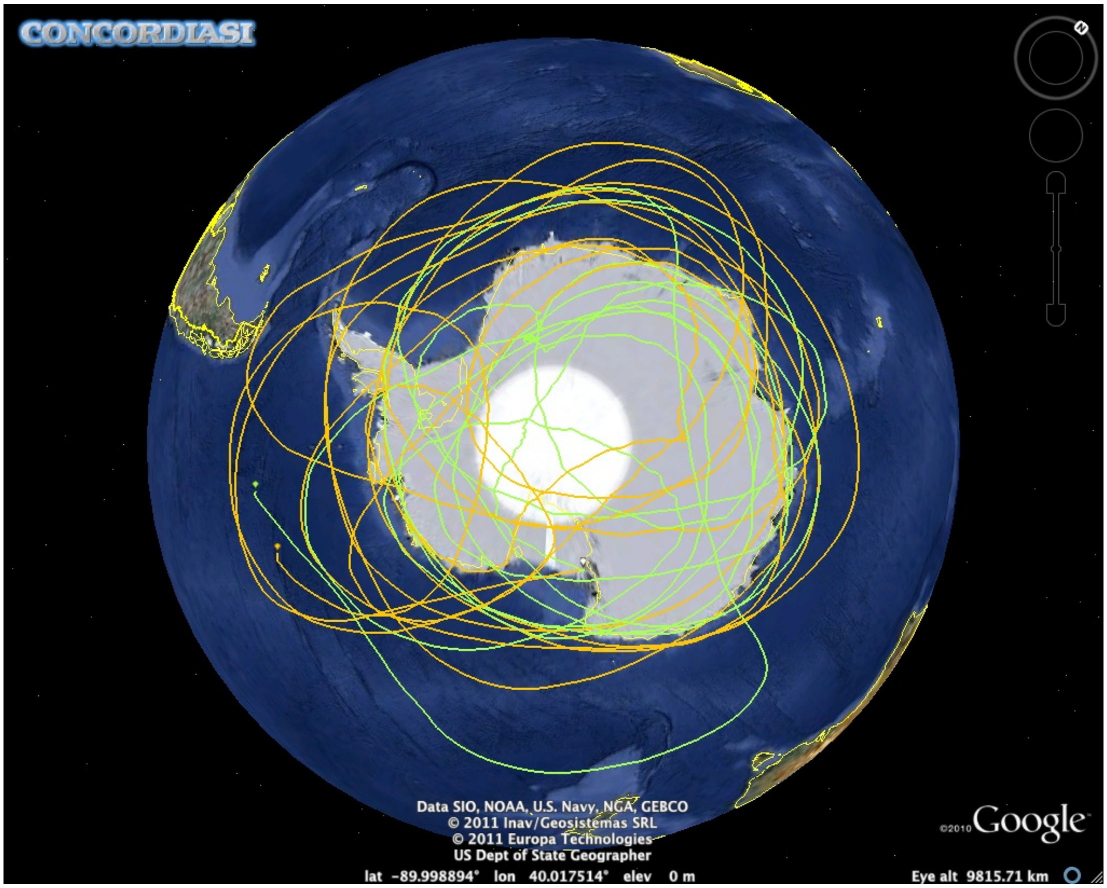

Figure 2 Balloon trajectories for PSC18 (green) and PSC19 (yellow) which carried the ROC instrument.

During the driftsonde portion of the campaign 647 dropsondes were released from 23 September through 8 December, deployed in clusters to optimize the overlap with IASI overpasses in support of the assimilation and IASI validation objectives. All balloons had flight level pressure and temperature observations. Dropsondes released in the proximity of the ROC balloon will be used to validate the ROC profiles.

GPS radio occultation theory

The balloon borne GPS radio occultation technique is based on the same principles as that used on low earth orbiting satellites, where recordings are made of signals from higher orbit GPS satellites as they set behind the Earth's limb (Kursinksi et al., 1997). As the line of sight of the GPS signal passes successively deeper into the atmosphere, the signal path is refracted (bent and delayed) as a function of atmospheric density. The refraction is measured by the Doppler shift of the carrier frequency of the GPS signal. From the atmospheric refractivity, information on the temperature and humidity structure of the atmosphere can be inferred. With the launch of the CHAMP (Hajj et al., 2004; Wickert et al., 2001), MetOP-GRAS (GRAS-SAG, 1998), the SAC-C (Hajj et al. 2004), and COSMIC (Rocken et al., 2000; Schreiner et al., 2007; Wu et al., 2005) radio occultation missions, the concept has reached an operational status with global coverage on the order of 3000 soundings per day. Previous studies showed the feasibility of performing similar measurements from high altitude aircraft (Healy et al., 2002; Lesne et al., 2002) that gives much more control in the locations of the soundings. We have developed and deployed a sounding system based on GPS receivers for the National Science Foundation HIAPER Research Aircraft (Garrison et al., 2007), and have now developed a similar system for stratospheric balloons.

The basic retrieval algorithm in its application to space-borne sounding is fully described in (Kursinski et al., 1997; Melbourne et al., 1994; Vorobev and Krasil'nikova, 1994). The refractive index of the neutral atmosphere at GPS frequencies is given by

$$N = (n-1)\times 10^{6} = 77.6\frac{P}{T} + 3.73\times 10^{5}\frac{P_w}{T} \quad \text{(T1)}$$

where N is refractivity, n is the refractive index, P is the atmospheric pressure in hPa, T is atmospheric temperature in Kelvin, and P_w is water vapor partial pressure in hPa.

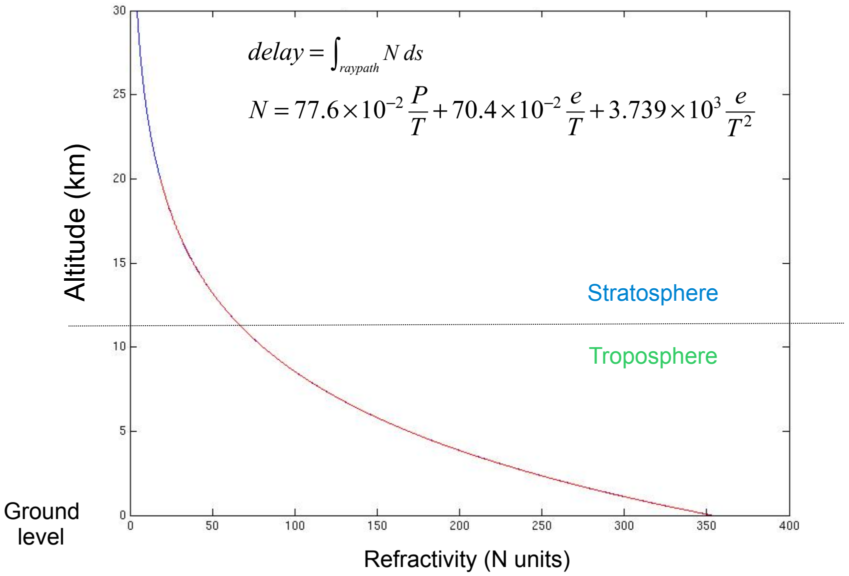

Figure 3 The delay in the GPS signal increases as the line of sight between the balloon and the satellite moves lower in the atmosphere.

With the GPS receiver located inside the Earth's atmosphere on a stratospheric balloon, the GPS occultation measurements must be corrected for the asymmetric sampling geometry by collecting data at both negative and positive elevations relative to the receiver's local horizon. Taking the difference between the negative bending angle α_N and the positive bending angle α_P, we get the "partial bending angle" as follows:

$$\alpha'(a) = \alpha_N(a) - \alpha_P(a) = -2a \int_{a}^{n_R r_R} \frac{d\left(\ln n\right)/dx}{\sqrt{x^2 - a^2}} dx \qquad \text{(T2)},$$

The refractivity below the receiver can then be retrieved through the Abel inversion, which is similar to the spaceborne GPS occultation case but includes consideration for the refractivity at the receiver:

$$n(r) = n_R \exp\left(\frac{1}{\pi} \int_{x(r)}^{n_R r_R} \frac{\alpha'(a)}{\sqrt{a^2 - x^2}} da \right) \qquad \text{(T3)}$$

The temperature and water vapor profiles can be retrieved from equation (T1) using 1Dvar techniques. On the other hand, bending angle or refractivity observations can be directly validated or assimilated into numerical models, thus avoiding the P_w *vs* T ambiguity (Eyre, 1994; Healy et al., 2005). Significant reduction of the errors in the temperature field in the upper troposphere and lower stratosphere has been observed when spaceborne refractivity profiles were assimilated into the UK Met Office NWP system (Healy et al., 2005). The assimilation of derived bending angle has been proven to have a positive impact at the ECMWF analysis (Healy and Thepaut, 2006). Other modeling centers have also demonstrated significant reduction of temperature and humidity errors for all latitudes over the globe after assimilating GPS occultation including over the Antarctic (Cucurull, 2006; Wee et al., 2008).

As a GPS satellite sets with respect to the Earth from the balloons point of view, we can sense the amount of water vapor present in the atmosphere by delays in the received signal

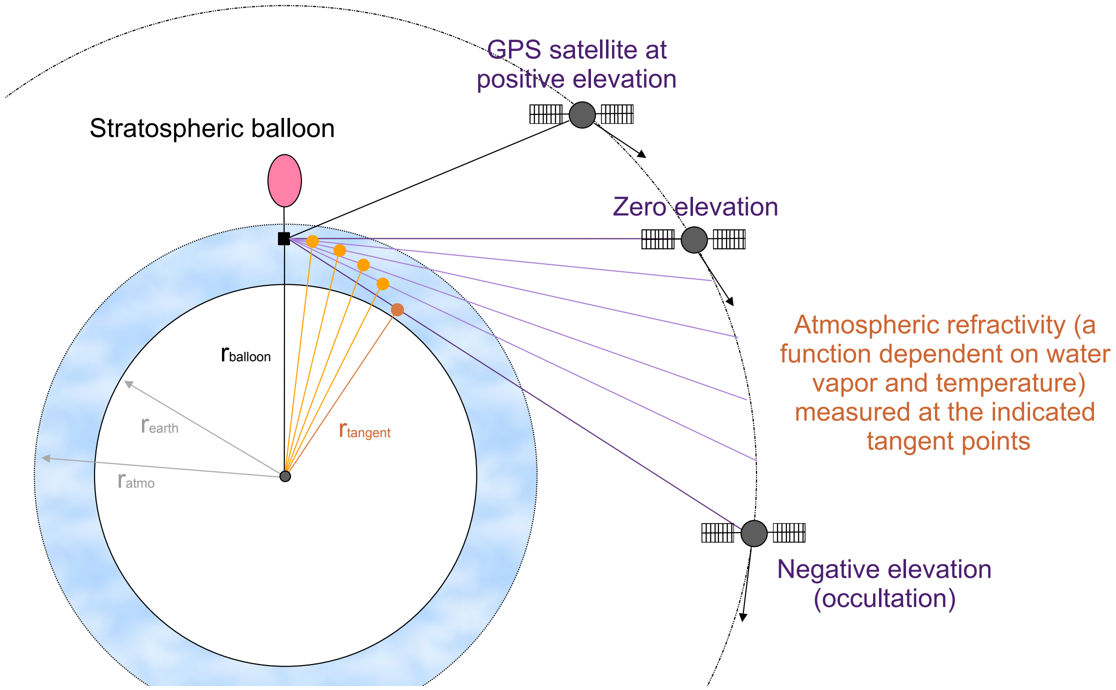

Figure 4 Schematic representation of the balloon-borne radio occultation geometry.

Simulations of Antarctic Radio Occultation Profiles

We have simulated radio occultation observations in order to determine the magnitude of the expected atmospheric signal, compared to assumptions about measurement system noise. Two radiosonde profiles from station Novalazarevskaya (#89512) at latitude 70.77S are used as examples of two different types of conditions, in January during the southern hemisphere summer, and in August during winter. We calculated the bending angle as a function of impact parameter for a receiver at 20 km altitude (Figure 5). We added simulated noise to the simulated Doppler shift, in this simple case random noise on the order of 2 mm/sec to represent uncertainties in the balloon velocity, which is approximately the value found for the aircraft case (Muradyan et al., 2009). We then retrieved the bending angle and refractivity as described above. Under these assumptions, the accuracy of the retrieved profiles is easily sufficient to distinguish the structures in the two profiles (Figure 5). This level of accuracy is also sufficient for examining the level of discrepancies between IASI retrievals and dropsondes found during the Seychelle campaign (Figure 6). We will investigate the balloon dynamics during the Concordiasi campaign with the precise positioning data and sampling strategies at different data rates to understand better the true error processes affecting the radio occultation data.

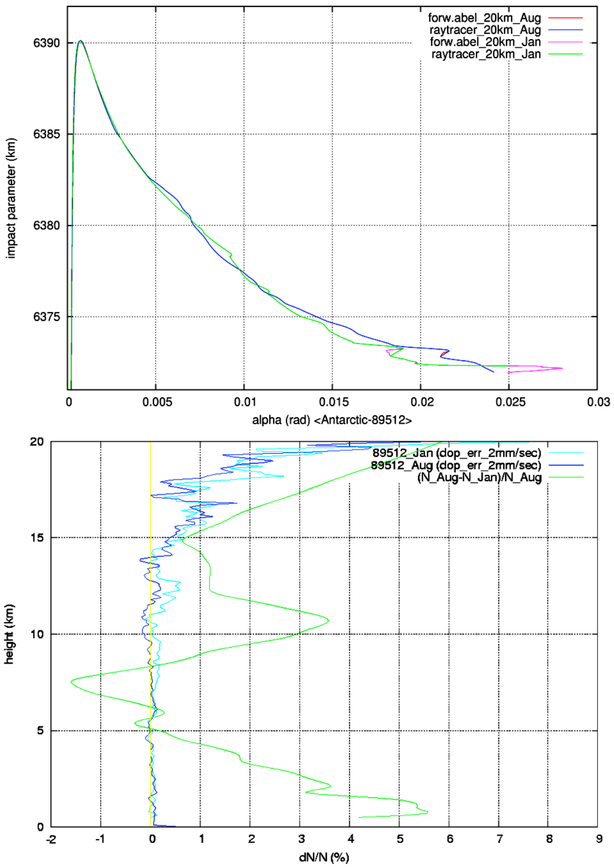

Figure 5 ((Left) Simulation of bending angle variations as a function of tangent point height for January and August soundings. Note the large increase and rapid variations in the bending as the signal passes deeper into the atmosphere. (Right) Estimates of the percentage refractivity retrieval errors for the January and August profiles (blue) assuming 2mm/sec errors. The green profile shows the refractivity difference (in percentage) between August and January, which is well outside the error bunds up to 15 km.

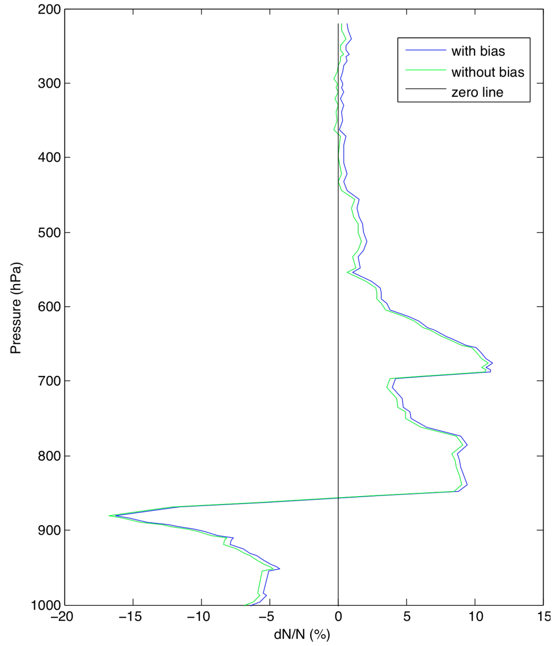

Figure 6 Difference in refractivity for (IASI retreival - dropsonde) and (IASI retrieval - dropsonde w/o bias).

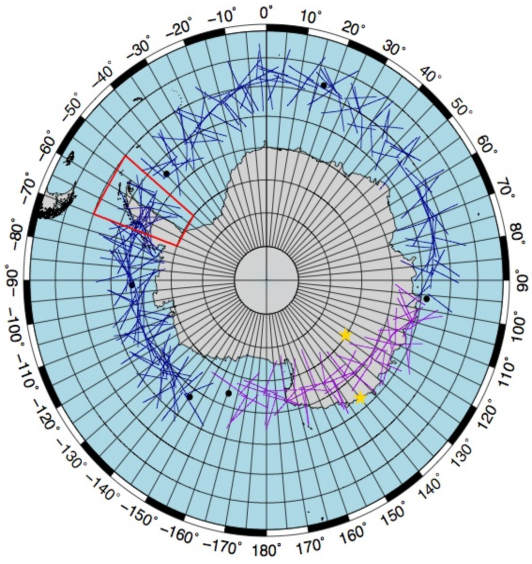

Figure 7 Simulation of the occultation sampling from 5 flight days Each blue line shows the horizontal drift of the tangent point for the occultation as the raypath descends in the atmosphere. Purple lines show the occultations over a period of one day. Red polygon shows target region for high rate positioning.

We have simulated the balloon occultation measurement distribution assuming a height of 19 km (Figure 7). In a typical six hour period, of the 10 occultations that occurred, data was retrieved for the best three occultations. The on-board software selects the best occultation to transmit based on geometry and signal strength. This compromise was chosen in order to remain within the bandwidth of the Iridium data link. The proof-of-concept was successful. Approximately 60 setting occultations per day were possible given the geometry. Work for future missions will address data compression or on-board processing algorithms that would allow a greater number of occultations to be transmitted.