NITRO Team's reply to the "Questions to the NITRO Team" by SARP

We thank the panel for the careful examination of our proposal, and the questions asked on it. Following are our answers, inserted after every question.

I. The review panel raises severe doubts that a successful determination of present days' nitrogen escape rate would allow valid conclusions on the nitrogen abundance of the Earth 4 billion years ago or on the reasons for the low nitrogen abundance on Mars.

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General answer to I: The observation of non-thermal escape of nitrogen is a mandatory step to examine any theory on the atmospheric formation of Earth/Mars/Venus and other planets/moons. For nitrogen, the total amount of N^+ escape over 4 billion years can be comparable to or higher than the present day's nitrogen inventory of the Earth (and much higher than present day's nitrogen inventory of Mars), because of the following reasons:

The total amount of nitrogen on Earth (the majority is in the atmosphere, where it constitutes 78% of it) is about 4-5 x 10^{18} kg. Consequently, if the non-thermal escape rate reaches 10^9 kg/year (10^{27} ions/s), one can no longer ignore the non-thermal nitrogen escape over the Earth history compared to the present days nitrogen inventory. To the present day's knowledge, heavy ion escape is of the order of 10^6 kg/year (Nilsson, 2011) and this amount varies by more than three orders of magnitude from geomagnetically quiet periods (quiet Sun) to magnetic storm times (active Sun), as shown in Figure 1 (Cully et al., 2003). For the content of these heavy ions, there is a very limited knowledge of the cold N^+ outflow above the ionosphere. The existing few measurements only indicate that the N/O ratio increases to nearly unity (or even more) during major geomagnetic storms (Yau et al., 1993).

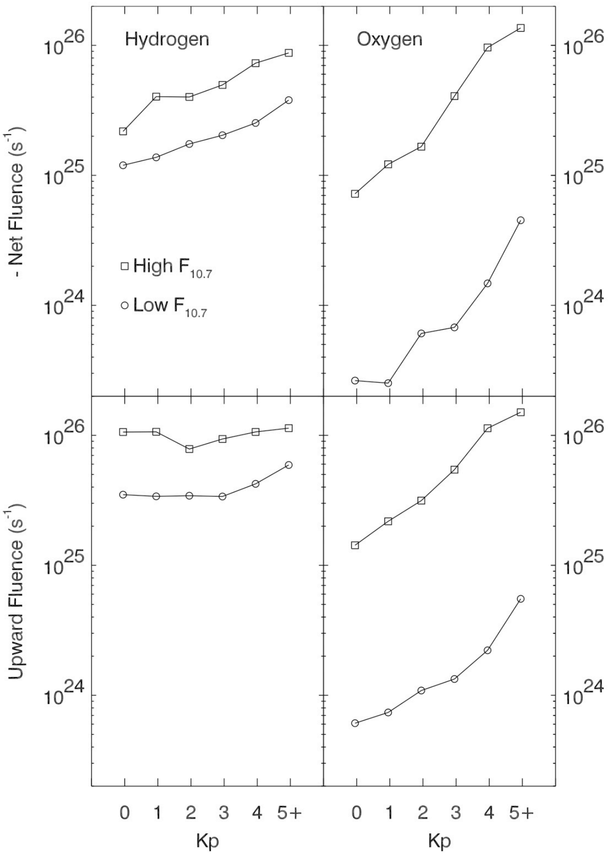

Figure 1: Satellite observation of the upflow flux of protons (marked as "Hydrogen") and heavy ions (marked as "Oxygen") for different geomagnetic activity levels at the energy range < 20 eV (Cully et al., 2003). Kp is a world-wide geomagnetic activity index calculated from geomagnetic data from 8 stations at around 45°-60°, and large Kp means high geomagnetic activity. F10.7 is an index that is used as a proxy for the solar EUV flux. The heavy ions are conventionally labeled O^+ but in reality they also contain N^+.

The young Sun (in a billion-year scale) was characterized by a higher solar EUV flux, a stronger interplanetary magnetic field (IMF), and a faster solar wind (due to faster solar rotation). As a consequence, the average non-thermal N^+ escape rate in the past could have been the same as (or even more than) the present day's maximum escape rate during major geomagnetic storms, under high EUV flux (Krauss et al., 2012). Therefore, the average nitrogen escape rate might rise even to 10^{10} kg/year or more, while it could be still as little as 10^7 to 10^8 kg/year. In the former case the non-thermal escape of nitrogen plays an essential role in the atmospheric evolution of the Earth. To have a good empirical estimation of the billion-year scale of non-thermal escape, we need a good knowledge of present days' nitrogen escape rate over a wide range of solar and solar wind energy inputs, particularly during large CME (Coronal Mass Ejection) events. This is one of the major objectives of the NITRO mission. The high escape rate is also inferred from the high nitrogen content of Venus, which is more than three times as much as that of Earth (3.5% of the 92 bar atmosphere of Venus). If Earth and Venus had the same amount of initial nitrogen inventory, Earth should have lost a considerably large amount of nitrogen by now.

This argument does not apply to oxygen escape because our knowledge of oxygen at Earth suggests that its escape rate is far below the amount required to affect the atmosphere (which has a good supply from the oceans). In other words, we are most likely loosing much more nitrogen than oxygen compared to their abundance, dispite the larger chemical stability of N_2 compared to O_2 (due to the different dissociation energy of these two molecules). Therefore, the nitrogen escape problem is more important than the oxygen escape for the planetary evolution viewpoint (except from the water searching viewpoint).

If the estimated total amount of non-thermal nitrogen escape from the observations indicates the same as (or more than) the present day's nitrogen inventory, we have two immediate implications on the on-going questions for the formation and history of the terrestrial/planetary atmospheres: (a) how the nitrogen atmosphere of the Earth formed, and (b) the interpretation of the different isotope ratios of volatiles (e.g., $^{15}N/^{14}N$, $^{17}O/^{16}O$, $^{18}O/^{16}O$, and D/H ratios).

(a) There are two major scenrios that explain the N_2 (and volatiles) inventory in the ancient Earth (and Venus). In the first scenario, comets and astroids that were formed at a long distance from the Sun are considered to have delivered N_2 to the Earth and/or Venus. The theoretical basis for such delivery models are (1) outgassed volatiles must have escaped from the planet within a short period, due to high surface temperatures (this is why outgassing occurs) and high solar EUV fluxes (this makes exospheric temperatures high enough to cause hydrodynamic loss of nitrogen); and (2) volatiles like N_2, NH_3, CO_2, or CO need extremely low temperatures to be condensed, as shown in Figure 2. Even considering the attachment to dust particles, it is difficult for those volatiles to be included into the proto-Earth at the Earth distance from the Sun. In fact, the nitrogen abundance in the solar system objects increases with distance from the Sun.

In this scenario, the required delivery flux increases as the estimated amount of nitrogen escape increases to compensate the additional nitrogen inventory that corresponds to the escaped one. If NITRO measurements show a large amount of total nitrogen escape, the required delivery fluxes would become beyond what the comet/asteroids could have delivered, and therefore the other model (see below) would become more appropriate.

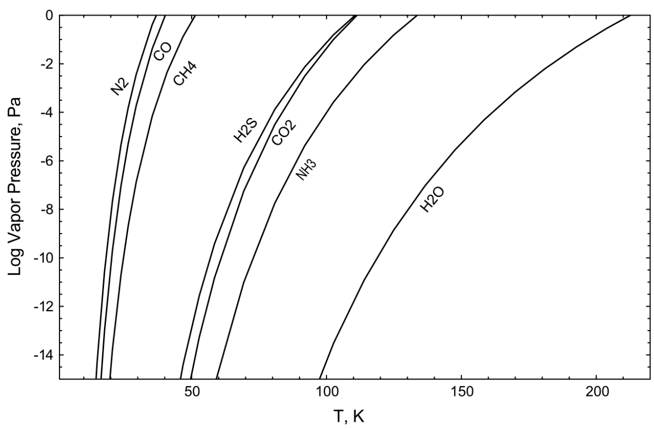

Figure 2: Equilibrium condensation temperature of volatiles. For lower pressure environments, liquid state does not exist, and the vapor pressure is directly given as a function of temperature of the frozen volatiles.

The other promising model is production of N_2 through outgassing of NH_3. In this case, a good mechanism is needed to protect NH_3 (or in the converted form of N_2) from hydrodynamic escape (cf., the argument (1) for the delivery scenario). According to the exospheric model by Lammer et al. (2013), a solar EUV flux only 7 times as high as the current value would be enough to trigger the hydrodynamic escape of the nitrogen atmosphere. In such a case, the present Earth would have very little nitrogen, like Mars has now. One effective method to protect from the hydrodynamic escape is the greenhouse effect (i.e., cooling of the exosphere as a return of warming close to the surface), but this model has a problem in protecting H_2O. If NITRO measurements show a large amount of total nitrogen escape, such a protection mechanism would become an essential element in the planetary formation models. This argument (protection from escape versus delivery) also applies to water.

(b) The different isotope ratios of volatiles between planets ($^{15}N/^{14}N$, $^{17}O/^{16}O$, $^{18}O/^{16}O$, and D/H) have often been used as indicators of the total amount of escape, compared to the initial inventory. The reason is that the scale height is counter-proportional to the mass for non-convective (stratospheric) air. In the present case, mass 28 and 29 are concerned, because of the molecular form.

This gravity-type mass-filtering certainly applies to Jeans escape (thermal escape) and most likely also to hydrodynamic escape (e.g. nitrogen escape dragged by hydrogen at Titan (Strobel, 2009)). However, there is no reason that the gravity-type mass-filtering can be applied to the non-thermal ion escape, because the velocity distribution of non-thermal ions is no longer a Maxwellian with zero mean values. The mass-filtering by gravitation force is much less effective for ion escape, if ever it has any effect, than for neutral escape. If the NITRO measurements show that non-thermal escape was the major player for the evolution of the terrestrial nitrogen atmosphere, different isotope ratios between different planets are better interpreted as: either (1) different escape mechanisms between different planets; or (2) different heights of the convection layer and altitudes where N_2 is ionized; or (3) caused by the planetary formation processes (e.g., back to solar nebula). In this case, the good correlation between the $^{15}N/^{14}N$ ratio and the D/H ratio, as shown in Figure 3 (Marty, 2012), suggests either a restrictive relation between the roles of the non-thermal escape and exobase height, or mass-filtering at the time of planetary formation. This would be certainly one step forward in understanding the Mars mystery.

<u>Measuring the non-thermal nitrogen escape at Earth today is thus very important for comparative planetology and for the interpretation of the isotope ratios</u>.

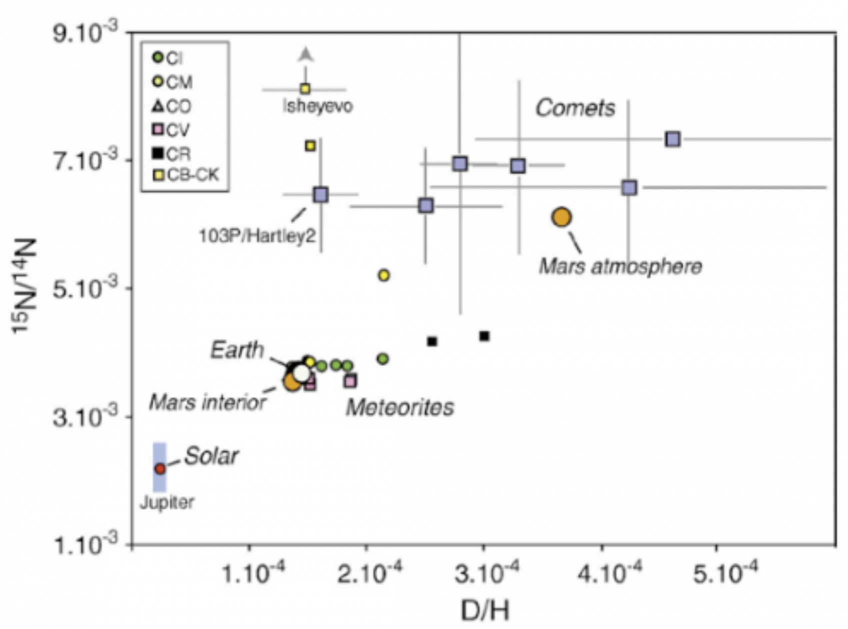

Figure 3: Observed isotope ratios of different solar system objects (Marty, 2012).

Q1. First, what are the prospects to determine at all the nitrogen escape rate in view of the hard to assess return flux into the atmosphere?
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A1: <u>The amount of return flux into the atmosphere is small</u>, and can easily be modelled by assuming adequate charge exchange rate (that can be tuned by comparing with observations) in the ion drift model. The majority of the outflowing ions, except cold ions directly entering the inner magnetosphere, ultimately escape due to following reasons (a)-(d):

(a) Heavy ions with escape velocity in the polar cap do not return. According to solid statistics, this amount is already larger than those of Mars or Venus, due mainly to the large interaction area of the Earth's magnetosphere with the solar wind (Nilsson et al., 2011).

(b) Heavy ions with escape velocity in the inner magnetosphere (both direct supplied and returning from the magnetotail) either drift to the dayside or charge exchange with neutrals. The formers are completely lost to the space after reaching the magnetopause, and more than half of the latter are directed outward from the Earth rather than toward the Earth. According to numerical simulations by Ebihara et al. (2006), return flux to the atmosphere will become negligible during large geomagnetic activity. According to the Freja observations, the return flux of heavy ions is very small (Yamauchi et al., 2005). Therefore, we just need to measure the fraction of cold N^+ that enters (or returns to) the inner magnetosphere. The 15-years old picture of "escaped ion returns to the atmosphere" is not correct according to Cluster observations and to numerical simulations (Nilsson et al., 2011; Haaland et al., 2012).

(c) The outflowing cold ions that enter the plasma sheet are adiabatically energized before reaching the inner magnetosphere, and the amount of heavy ions that stays cold (< 10 keV) is negligible compared to the energized ions, according to both the Cluster observations and to numerical simulations (Yamauchi et al., 2009).

(d) Finally, outflowing cold ions in the polar cap are expected to escape after experiencing centrifugal acceleration (Nilsson et al., 2008).

Therefore, the return amount of nitrogen is very small if the nitrogen ions are already energized above the escape velocity (>10 eV). The "return amount to the atmosphere" matters for the fraction of outflowing cold ions that directly enter into the inner magnetosphere. Cluster observations found many of them (Yamauchi et al., 2013), and the fate of these ions is unknown. However, pitch angle information from the NITRO instruments will indicate whether these "nearly field-aligned" ions return to the atmosphere or not. Meanwhile, NITRO will also measure energized ions within the inner magnetosphere, that will not return to the atmosphere. Estimation of the fate of ions directly entering into the inner magnetosphere can thus be deduced from the pitch-angle information. This is why the apogee of the in-situ spacecraft is set around 5 to 6 R_E. The mission must cover this region, to have the best estimate of the returning ion fluxes to the atmosphere. Since the proposed in-situ spacecraft has a high-inclination orbit, the spacecraft covers the magnetic latitudes where the majority of ion flows, relevant to the escape and return, are found.

Regarding the orbit coverage:

In the two spacecraft option, the in-situ spacecraft (inclination=68.5°) covers well the lobe region, through which ions get into the magnetotail (and the majority of them finally escape, as mentioned above). In addition, the remote sensing spacecraft will cover the entire polar cap.

For the one spacecraft option, we would set the inclination to about 80° to 90°, instead of 68.5°, such that the spacecraft covers the polar cap. The reason why the 68.5° inclination was selected (for the two spacecraft option) was to provide the same longitudinal drift between the two spacecraft. Such a restriction does not apply to the one-spacecraft option. A higher inclination here increases the latitudinal drift of the orbit axis, covering all altitudes within the 3 year mission lifetime (i = 75° means a latitudinal drift of about 3°/month, and i = 80° means about 4°/month instead of 2°/month for i = 69°).

Q2. Are there any other potential applications of the intended measurements to open questions on other planetary atmospheres?
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A2: As described above (General answer to I), characterising and quantifying the non-thermal nitrogen escape for various solar conditions provides restrictions and boundary conditions for models of the formation of a nitrogen atmosphere and its history at the Earth and at other planets, as well as for the interpretation of the $^{15}N/^{14}N$ ratio.

II. The design of the one-spacecraft option, neither the instrument configuration nor the measurement strategy, is well described in the proposal. The proposing team is asked to provide this information. Furthermore:
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General Answer to II: Accommodation of NUVO for the one-spacecraft option is drawn in Figure 4 (same as Figure 4.5 of the proposal, except that the FOV (field of view) direction is here included). If NUVO were placed on the in-situ spacecraft, it would occupy the open spot and would look outward. Since the spacecraft is Sun-pointing, and the spin period is slow (22-26 sec), NUVO would not need any scanner to cover 360° in the direction perpendicular to the Sun-Earth line (Y-Z plane in the coordinate where X direction is defined as the Sun direction looking from the Earth). Since the required temporal resolution (which also is

linked to the spatial resolution) is about 2 min, the observations in the same direction could then be integrated over 5 spins.

The orbit parameters would also be different (inclination of about 80° instead of 68.5°, as mentioned above). The required time resolution (2 min) and the spin period (22-26 sec) would remain unchanged.

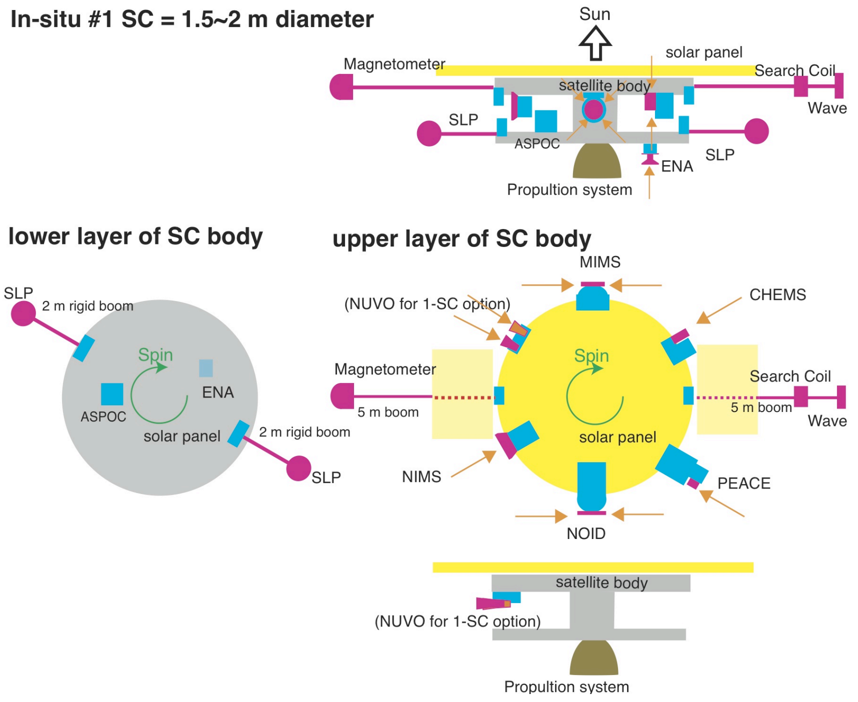

Figure 4: Accommodation of science instruments for the one-spacecraft option. NUVO is placed in the vacant spot of the in-situ spacecraft for the two-spacecraft option. Field-of-view (FOV) is given by orange arrows.

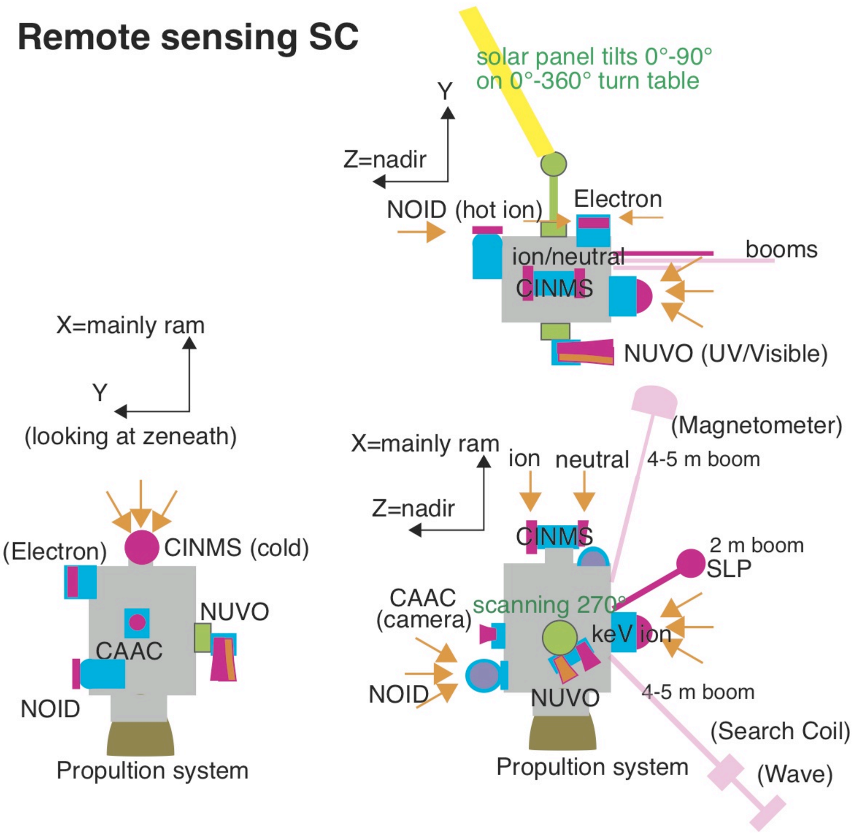

Figure 5: Accommodation of science instruments on the remote-sensing spacecraft for the full payload including all optional scientific instruments. The satellite surface where NUVO is placed is clear from any other instrument or spacecraft structure.

Q3. What will be the position of the remote sensing instrument NUVO relative to the particle detectors and the booms?
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A3: Figure 5 shows the proposed accommodation for the full size option. No particle instrument blocks the NUVO FOV, and even no boom or solar panel blocks this NUVO FOV.

Q4. What pointing strategy will be adopted to reach the goal of simultaneous assessment of nitrogen escape from the ionosphere and its flux in the magnetosphere?
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A4: When the in-situ spacecraft will be within the scanning plane of NUVO, there will be several options of scanning modes that cover the magnetosphere, including the in-situ spacecraft, because the required temporal resolution of local phenomena at the in-situ spacecraft (>2 min) is slower than the NUVO duty cycle time (few sec). The scanner moving angle is by 1° to up to 10° steps. The 10° step option is for scanning the full angular range of the scanner (270°). The 2° step option is for a continuous (no gap in the covered FOV) scan. The 1° step option is for the best angular resolution. Since the fastest measurement is 2 sec, the 2-min time resolution for a full scan leads to 60° or 120° coverage angle (for the 1° or 2° step option, respectively). That is enough to cover a large area within the magnetosphere, including the in-situ spacecraft. The integration time can be increased up to a maximum of 100 sec by narrowing the full scan width, because the in-situ spacecraft moves by only 0.3° viewing angle from the Earth during the 2-min duty cycle of NUVO when the spacecraft is located near the apogee, as illustrated in Figure 6.

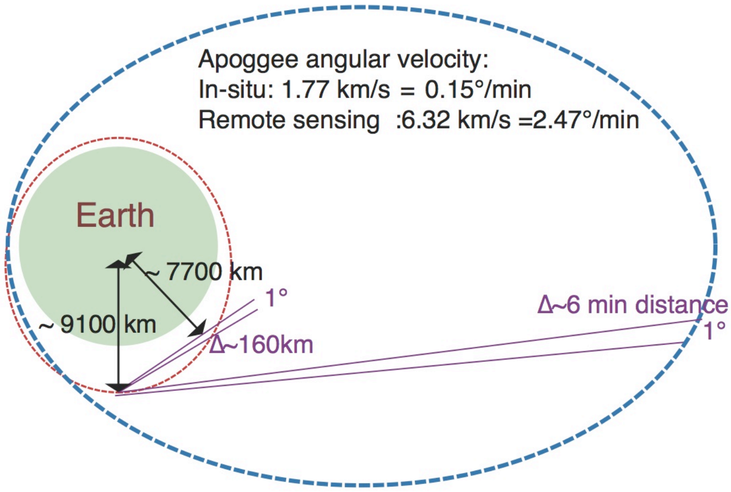

Figure 6: FOV direction of NUVO from the apogee of the remote-sensing spacecraft. When targeting at 1000 km high in the limb direction, a 1° angle corresponds to about 160 km distance (cf. NUVO's best angular resolution is 0.1°). When targeting at the in-situ spacecraft, a 1° angle corresponds to about 6-min travel distance of spacecraft near its apogee (the in-stu spacecraft moves only 0.15°/min in viewing angle from the Earth when it is at its apogee).

When the in-situ spacecraft is outside the scanning plane of NUVO, the duty cycle can be increased to more than 3 min, such that the average profiles can be obtained. In this case, we have observation modes in which the FOV stays in one direction (e.g. limb observation), or scans in altitude. Since the orbit is elliptic, even a fixed-angle operation mode (no scanner operation) would gradually sweep the different altitudes as the spacecraft slowly changes its attitude (this is another advantage of the elliptic orbit). Alternatively, we can change the scanner angle every few minutes to sweep the same altitude in every duty cycle, in order to look at the latitudinal dependence.

In both cases, NUVO could have a long integration time for higher accuracy. Thus, both the latitudinal scan and the altitude scan for average intensity are possible when the in-situ spacecraft is not visible from the remote sensing spacecraft.

Q5. Will sensitivity and angular resolution of NUVO be sufficient for determining the nitrogen constituent of the exosphere above 1000 km, when the S/C is near apogee?
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A5: Yes it is. The intrinsic angular resolution of the NUVO instrument is 0.1°. The 2° viewing angle of NUVO is for a total of 20 slits. The altitude resolution, when we take the 1°scanner step and take limb observation targeting at around 1000 km altitude, is about 160 km, as shown in Figure 6. The 1° resolution corresponds to about 30 sec for the spacecraft to change its attitude, and 30 sec is long enough to expect adequate counting statistics. This is already sufficient to obtain a useful exospheric profile, e.g., to test against exospheric models. Since we expect a higher column density for limb observation than for the configuration looking outward toward the in-situ spacecraft, a 3-sec resolution (0.1° change in attitude) is possible, allowing a total FOV of 2° with 1° scanning and a 0.1° resolution (maximum resolution of NUVO). This corresponds to a 16 km altitude resolution. Furthermore, CINMS will make direct in-situ measurements of the populations in the lower exosphere, that can be compared with the NUVO column-integrated observations, assuming steady state.

Concerning the sensitivity, NUVO can change its integration time from 0.1 sec to 100 sec and has therefore a wide dynamic range. Since long integration time is allowed for both periods when the in-situ spacecraft is visible from NUVO and when it is not visible, NUVO has a wide operational dynamic range, allowing sufficient sensitivity. A lowest count rate is expected when the spacecraft looks outward rather than towards the limb (Figure 6). Even in that case we expect a 10^9 cm^{-2} column integrated nitrogen density in the magnetosphere, during storm times, excluding the plasmaspheric content. This value is high enough to be detected by NUVO.

III. Establishing the dependence of the N^+/O^+ ratio on solar activity is a main goal of the proposed mission.
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General Answer to III: Yes it is. <u>The purpose is to understand nitrogen circulation that is much more poorly understood than that of oxygen</u>, although it is a very abundant element, after Hydrogen and Oxygen, and is <u>essential for life</u>. As mentioned earlier, nitrogen escape and circulation is strongly linked to solar activity.

Q6. Will the amplitudes of the solar activity variations to be expected during a three years mission be sufficient to establish the desired dependences?
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A6: Yes it is, because we expect that the mission life time corresponds to the declining phase of the next solar cycle #25, with a good margin. As shown in Figure 7, two years in the declining phase are in principle enough to provide a large amplitude in the F10.7 index (a proxy for the solar EUV flux). This also applies to the solar wind velocity because the recurrence pattern and many large CMEs are mixed during this period. Particularly many large events, which are the most important for estimating the escape rate for Earth-Sun

analogy (Krauss et al., 2012), occur within a period of about 1 year (1974, 1982, 1994, and 2003) during each solar cycle, as shown in Figure 8 (Yamauchi, 2015). At the moment, we have just passed the second peak of sunspot activity in early 2014. Considering the currently longer solar cycle than previous cycles, declining phase peak year is expected sometime in 2027-2028. This is well included in the mission period, even if the mission were delayed by 1 or 2 years. The next opportunity would be the following inclining phase, which probably will start around 2030.

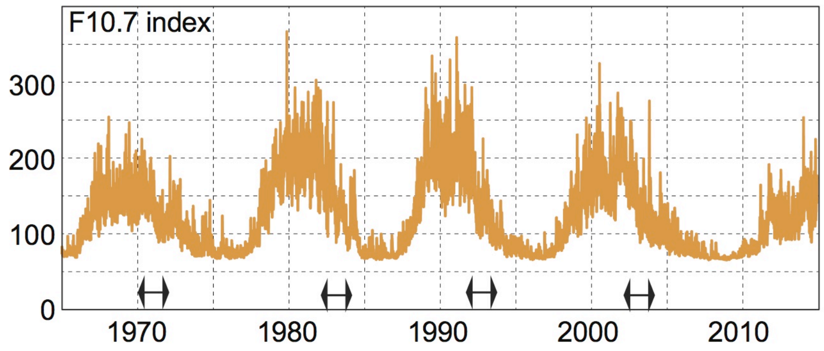

Figure 7: Past 50 years data of F10.7 index (daily value), which is a proxy for the solar EUV flux (Yamauchi, 2015).

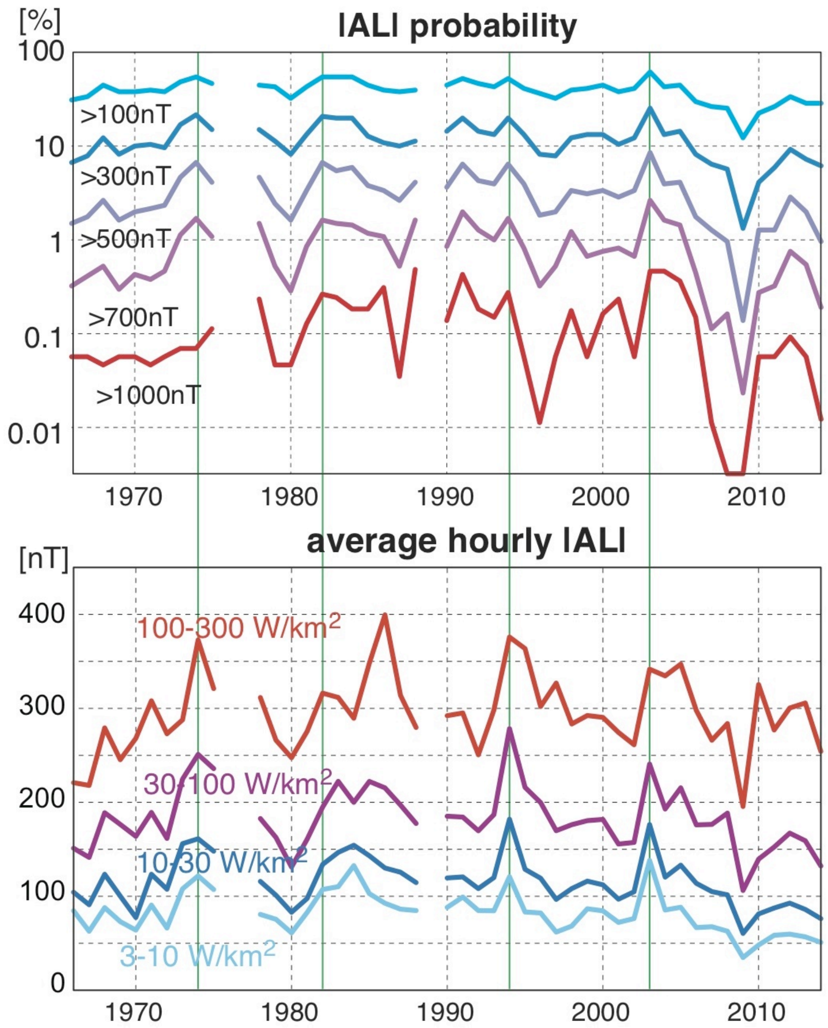

Figure 8: Upper panel: Past 50 years data of annual averages of AL index (a world-wide geomagnetic index calculated from geomagnetic data from 11 stations at around 65-70°, at which latitude the geomagnetic disturbances is normally the largest in the negative direction). The probability of more than a certain activity is plotted. Lower panel: Past 50 years data of annual averages of Sun-Earth coupling efficiency, i.e., average AL for the same solar wind electromagnetic energy input condition (Yamauchi, 2015). For each solar cycle, one-year peak is recognized during the declining phase, as indicated by green vertical allows.

IV. The design of the booms accommodating the Langmuir probes is left as optional between lengths of 1.75 m outside the (highly variable) spacecraft sheath and 50 m tip-to-tip.

Q7. What boom configuration is regarded as appropriate to monitor the d.c. and low-frequency electric fields which give insights into the plasma dynamics and particle acceleration?
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A7: The shortest configuration (tip at 1.75 m from the spacecraft body) is the baseline, and it provides the DC satellite potential with 1-2 V accuracy. This configuration also provides information on the electrostatic emissions and on the Poynting flux propagation of the electromagnetic emissions. This <u>fulfills the mission scientific objectives (ion cyclotron waves and low hybrid waves)</u>. The longer boom option, such as 4-5 m (as recommended by Göran Marklund, Royal Institute of Technology) gives more wave modes. Such studies are considered as "bonus science" (that is the reason why a single E-field component is measured). The longest boom option (wire booms) allows the probes to stick outside the spacecraft sheath during a larger portion of the orbit.

Q8. Which institution inside the consortium possesses the technology for long wire booms and would be ready to provide them?
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A8: Tohoku university (CAAC PI) has the technology, but they (Dr. Kasaba) have not yet considered building such a subsystem for NITRO. As written in the proposal, the long wire boom is not included in the baseline and it is an option. We consider it only in the case extra budget would be available (particularly for the one-spacecraft option, where the cost of the second spacecraft would be saved).

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