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Interactive comment on “Daedalus: A Low-Flying Spacecraft for the Exploration of the Lower Thermosphere - Ionosphere” *by* Theodoros E. Sarris et al.

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Replies to Reviewer 1 Comments

We thank the reviewer for an extremely thorough evaluation of the manuscript. We agree with all comments raised, and have addressed them extensively. The paper is now significantly updated, with new figures, references and sections added, as described in the following:

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Reviewer 1 Comment 1:

1.1 Comment from Reviewer:

“the manuscript has been written very much in the same style as we all write our money proposals. For example, the Conclusions is more like a selling document than a concise review of the major findings from the mission preparatory work. I kindly ask the authors to make an attempt for a more objective rhetoric at least in the points which I discuss later in this report”

1.2 Author’s response:

–> We agree that the statements in Section 5.3 do not provide any additional information; furthermore, the previous Section (5.2) includes both Discussion and Conclusions, with an objective rhetoric that includes references to areas where Daedalus will have impact. Thus a second conclusions paragraph was redundant. We have therefore removed this section altogether.

–> Furthermore, as also requested by the second reviewer, scientific background is enhanced by providing and discussing a number of references, on Joule heating, Sub-satellite payloads, TEC, etc, as follows:

1.3 Author’s changes in manuscript:

–> Section 5.3 has been removed

–> The following references on modeling of Joule Heating have been added:

Hernandez et al.,2005; Lopez et al., 2004; Connor et al., 2016; Slinker et al., 1999

–> The following references on scientific justification for Sub-Satellite Payloads have been added:

Breneman, A. et al., 2017; Crowley et al., 2010; Crew, A. B., et al., 2016; Crowley et al., 2011; Fish et al., 2014; Hoang et al., (2019);Kestila et al., (2013); Li, X., et al. (2013); Stromberg, et al., 2011; Westerhoff et al., (2015).

–> The following references supporting the discussion on TEC measurements have been added:

Alizadeh et al., (2011); Heise et al. (2002); Klobuchar, 1996; Park et al., (2017).

–> We have also restructured the paper and removed figures that are not adding to the scientific justification (Figure 1 and Figure 15).

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Reviewer 1 Comment 2:

2.1 Comment from Reviewer:

It remains somewhat unclear how consistent the requirements by modelling/simulations are with the performance of the instruments that will come as the heritage from previous missions. Some upgrading of the measurements' performance can be anticipated from today's state-of-art until the days of Daedalus instrument building, but how much such upgrading is needed? In particular, like Section 4.3.5 explains, very high precision in satellite pointing direction will be needed for accurate Joule heating estimates. For us readers it would be valuable to know, whether e.g. GOCE has reached such accuracy in its pointing direction that will be needed for Daedalus.

2.2 Author's response:

–> Daedalus will perform measurements in the under-sampled upper atmosphere, and some upgrading of the measurements' performance can be anticipated from today's state-of-art until the days of Daedalus instrument building. However we note that for many instruments the signal-to-noise ratio will be favorable in the higher-density upper atmosphere than measurements that are currently performed in space. Some upgrading is needed to achieve higher sampling times, needed in order to sample small-scale variations with a high orbital velocity as expected at Daedalus perigee locations (∼8 km/s). A relevant sentence discussing the above has been added in Section 4.3.5 in

the revised manuscript.

2.3 Author's changes in manuscript:

Page 33, lines 13-17: "It is noted that for many instruments the signal-to-noise ratio will be favourable in the higher-density upper atmosphere than measurements that are currently performed in space. Some upgrading of the instruments' performance is anticipated to achieve higher sampling rates, needed in order to sample small-scale variations with a high orbital velocity as expected at Daedalus' perigee locations (∼8 km/s)."

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Reviewer 1 Comment 3:

3.1 Comments from Reviewer:

Along the same lines, CO2 content in LTI is mentioned in Section 5.1 as one of the primary targets by Daedalus, while in the description of NMS CO2 is mentioned only as an desirable constituent in parenthesis and the values given in Table 2 for CO2 are difficult to compare with the ppm values given by some other studies on thermospheric CO2 contents (e.g. by Emmert et al., 2012).

3.2 Author's response:

Concerning CO2, according to the paper by Emmert et al., we should expect, at 110-120 km, around 50 ppm of CO2. Considering that the thermosphere, at these altitudes, is dominated by N2, which is around or above 10ˆ12 cmˆ-3, we should expect something around 10ˆ7 (or above) cmˆ-3 of CO2, so it should be within measurement range. However, this needs to be evaluated based on further information and updated instrument requirements. We have thus removed from section 5.1 the reference to CO2 as a primary target.

3.3 Author's changes in manuscript:

Reference to CO2 has been removed from page 37, line 13.

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Reviewer 1 Comment 4:

4.1 Comments from Reviewer:

While the heritage of Daedalus mother satellite instrumentation is explained carefully, the description of the cubesat instruments is rather cursory. Most likely the largest technology challenges will be in this part of the mission. As cubesats will have crucial role in accomplishing the breakthrough science by Daedalus, it would be good have a more thorough assessment about the ideal (goal) versus most potential (threshold) payload for the cubesats. I understand that most of the validation and testing work to define the final payload is still ahead, but the proposing team has probably already now collected some knowledge about the performance of miniaturized instruments versus the requirements given in Table 2?

4.2 Author's response:

–> Indeed, this part was not discussed in detail in the originally submitted paper; we have revisited this discussion, which is now greatly enhanced with scientific objectives, prioritization of the instruments and a detailed list in Table 3 of instruments that have flown or that are in a state of development. The following detailed discussion has been added in Section 4.2.9, "Sub-satellite Instrumentation" in response to the cubesat instrument selection, status of development and prioritization:

4.3 Author's changes in manuscript:

As discussed above in Section 3.3, Joule heating is expected to maximize in the altitude region around 120 km. As discussed in Section 4.1 of the Mission Orbital Design, the main Daedalus spacecraft will be able to estimate Joule heating by measuring E, B, un, Nn, Ne, Ni, and Te in-situ at these altitudes during the perigee descent campaigns. The main science objective of the deployed sub-satellites is to provide measurements

that will enable (a) a differentiation between temporal and spatial effects of the measured parameters while both the main spacecraft and the sub-satellite are at 120 km; (b) a second point of measurements at 120 km while the main spacecraft ascends to higher altitudes, after the dipping campaign is competed, which will provide estimates of the vertical gradients of Joule heating, and (c) measurements below 120 as perigee decreases. In the following we discuss the prioritization of context measurements that can be provided by the sub-satellites, and a preliminary assessment of their feasibility. Out of the measurements that are required to obtain Joule heating, as discussed above analytically, the electric field at an altitude of 118 km can be about 20 mV/m (Kirkwood et al 1988), while above 200 km they can be in the order of 20-40 mV/m (Davies and Lester (1999). Electric fields vanish below the altitude region where σP maximizes. The exact profile of E between 140 km and the altitude of maximum σP is not known. Since the electric field is introduced into the JH equation as squared, it is expected to have a considerable impact if it is not measured properly at low altitudes. Thus E is a key parameter to measure at a second point below the perigee altitudes of the main satellite, at altitudes of maximum σP. Neutral density, Nn, and neutral wind velocity, un vary significantly between the 140 km region and the region where σP maximizes (e.g., Cai et al., 2013); Nn affects the collision frequencies and un is directly related to qj. The consequences to the overall estimation of the Joule heating are thus also considered to be considerable. Electron density, Ne and ion density, Ni can reasonably assumed to be the same in this region. They can vary noticeably between the 140 km and altitudes of maximum σP (up to a factor of 2-5, based on TRANSCAR simulations; see, e.g., Blelly et al., 2005). Since these parameters go to the collision frequency estimation, which is also a function of Nn, their role can not be neglected, but maybe they are of secondary importance compared to E, Nn and un for Joule heating estimations. However, their role is significant as a proxy for EPP estimations, and simultaneous measurements of Ne at different altitudes along the same orbit (even with the implications of the phase difference between the two satellites, as described in Section 4.3.5 below) can provide significant improvements to current models that are used as proxy for EPP, such as the Rees et al. model, by improving the assumptions made therein (see, e.g., Schunk and Nagy, and Semeter and Kamalabadi, 2005). Furthermore, in-situ measurements of Ne would also be relevant for studying ionization and the energy input by solar EUV. For example, Lin and Chu (2017) recently performed an extensive modeling, but could only compare to the $\sim$40 year old AE-C data, which reached down to 135 km. The combination of Ne from the main satellite at 150 km perigee and the sub-satellite at 120 km perigee would provide a novel dataset from which to improve such modeling. Finally, measurement of the magnetic field, B, is important for Joule heating estimations, but not critical, as models of the magnetic field at these altitudes are considered to have high fidelity. In the following we discuss the maturity of miniaturized instrumentation for the above parameters. The technology for nanosatellites based on the CubeSat paradigm is advancing at a very rapid speed. With much improved capabilities and reliability over the last decade has also followed the demonstration of the utility of CubeSat-based missions for a broad range of applications [see e.g. Zurbuchen et al., 2017]. Consolidation of the observational requirements will dictate the observational requirements also for the sub-satellites, and further analysis and prioritisation of the science questions will determine for which parameters the extended lower altitude coverage is most essential and can be supplied by a CubeSat. Currently, most, but not quite all, of the above listed parameters have well-proven instrument solutions. Based on currently demonstrated capabilities and new capabilities that are in advanced state of development, the feasibility of achieving measurements required for Daedalus from a CubeSat-based platform is summarized in Table 3, including a classification in terms of expected advancement by the time of Daedalus' launch, names of corresponding missions and references pointing to the status of development. In this table it can be seen that, in particular, measurements of Ne, Nn, Ti and composition of ion and neutral species, as well as measurements of the magnetic field all have proven, or well-advanced development solutions for miniaturized platforms, including CubeSats. Regarding Electric fields, an instrument based on the double-probe technique has been developed for a multi-satellite mission concept, and is likely to be

demonstrated within the timeframe of the development of Daedalus (e.g., Crowley et al., 2015). Recent developments in the miniaturization of neutral wind instruments indicate that un measurements are also likely to be enabled onboard CubeSat platforms in the near future (Rod Heelis, personal communication, 2019). These measurements, therefore, constitute high-priority objectives that are considered to be feasible for the Daedalus CubeSats.

–>Table 3 has been added in the revised manuscript.

–> The following References have been added:

Crowley et al., 2010; Stromberg, 2011; Crowley et al., 2011; Fish et al., 2014; Crew et al., 2016; Breneman et al., 2017; Li et al. (2013); Kestila et al., 2013; Westerhoff et al., 2015; Paschalidis et al., 2018

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Reviewer 1 Comment 5:

5.1 Comment from Reviewer:

Unprecedented information on altitude gradients in several LTI parameters will be achieved by the combination of the Daedalus mother satellite and its cubesats. As the cubesats will have a slightly different orbit as the mother, the spacecraft will not always probe the same lat-lon regions simultaneously. According to Section 4.3.4 the maximum offset between the measurements by the mother and by the cubes is 60 mins. In stormy conditions 60 mins is a rather long time for the assumption of semi-simultaneous observations, like Fig 3 of this manuscript demonstrates (by four-time increase in Joule heating during one hour). A valuable exercise for this manuscript (and for the next rounds of Daedalus concept validation in ESA) would be to find out how often the mother and cubesats can provide altitude gradients with the demand of simultaneous measurements in the windows of, e.g., 10, 20, and 30 mins.

5.2 Author's response:

We thank the reviewer for this comment, which is indeed critical information for the conjunctions between the main satellite and the sub-satellites. A figure has been added with simulations of the time differences corresponding to the phase differences between the main satellite and the sub-satellites, as Figure 18b. A new section has been added with a relevant discussion, as follows:

5.3 Author's changes in manuscript:

Section 4.3.4: Temporal Coverage and Temporal Resolution

Regarding the aforementioned coverage related issues, simulations of conjunctions of the main satellite with the released subsatellite were performed. After the release of the subsatellite and the execution of the dip-out maneuver of the main satellite, Daedalus will orbit at its nominal perigee of 150 km and the subsatellite will follow a similar orbit at a lower perigee altitude of 120 km. As the subsatellite will have a shorter orbital period, the two satellites will be in and out of phase periodically, as shown in Fig18a. For the simulated scenario the expected lifetime of the subsatellite was calculated at 26 days, which corresponds to 314 orbits of the main spacecraft, thus the subsatellite will cross the main spacecraft's perigee latitude and subsequently the main spacecraft will follow with a temporal offset in the range of 0-58min. Temporal offsets were binned in windows of five minutes and the total number of orbital conjunctions over similar perigee latitudes were estimated in order to quantify the temporal offsets with which the main satellite and the sub-satellites will be able to provide altitude gradients. The results are presented in Fig. 18b. It is noted that, as demonstrated in Fig. 2, during storm-time conditions, increases in Joule heating by a factor up to 4 can be observed within a 60 min period. Thus temporal separations of a fraction of this period could meet the assumption of semi- simultaneous observations. As Fig. 18b demonstrates, there will be a significant number of orbits in the temporal offset window of <10 min (76 orbits). However this is dependent on the condition that the dipping maneuver and the subsequent release of a sub-satellite can be synchronized to occur during a storm-time event. This leads to additional requirements for the mission in terms of the minimum lead-time for the performance of a dipping maneuver and the release of a sub-satellite, will be investigated in the course of the upcoming phases of the proposed mission.

Figure 18: Temporal offsets between the main satellite and a released sub satellite are binned in time windows with 5-min increments, and the cumulative number of orbits within each window are plotted as a function of the temporal offsets.

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Reviewer 1 Comment 6:

6.1 Comment from Reviewer:

A suggestion for the title: “Daedalus: A spacecraft for in-situ exploration of the Lower Thermosphere-Ionosphere”

6.2 Author's response:

–> We thank the reviewer for this very appropriate recommendation; it is accepted and the title has been changed.

6.3 Author's changes in manuscript:

In the revised manuscript the title has been changed to: “Daedalus: A Low-Flying Spacecraft for in-situ Exploration of the Lower Thermosphere – Ionosphere”

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Reviewer 1 Comment 7:

7.1 Comment from Reviewer:

Page 1, line 35: “. . .orders of magnitude between models” -> “. . .orders of magnitude between models and observation methods”

7.2 Author's response and 7.3 Author's changes in manuscript:

–> Correction has been implemented in page 1, line 35-36.

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Reviewer 1 Comment 8:

8.1 Comment from Reviewer:

Page 3, line 17: Please explain the acronym PPOD

8.2 Author's response and 8.3 Author's changes in manuscript:

–> PPOD stands for "Poly-Picosatellite Orbital Deployer"; acronym has been explained in page 3, line 16-17.

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Reviewer 1 Comment 9:

9.1 Comment from Reviewer:

Page 5, line 26: When talking about rapid energy releases in the solar wind – magnetosphere – ionosphere system, it is good to remember also the abrupt penetration of magnetospheric electric field to dayside equatorial ionosphere during geomagnetic storms (see e.g. Kikuchi et al., JGR, 2008). Daedalus measurements will most likely be useful also in that research topic.

9.2 Author's response:

–> Thank you for this comment, we realize we have used obscure language in Table 1; we do not mean rapid energy release, but energy deposition.

9.3 Author's changes in manuscript:

We have corrected the wording to say "energy deposition" both in the text (page 6, line 3) and in Table 1 caption.

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Reviewer 1 Comment 10:

10.1 Comment from Reviewer:

Page 9: The purpose section 2.1.3 remains unclear to me. The section seems to repeat quite much the message of the questions posed in page 7.

10.2 Author's response and 10.3 Author's changes in manuscript:

–> This section has been removed, as it is indeed repeated elsewhere in the manuscript

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Reviewer 1 Comment 11:

11.1 Comment from Reviewer:

Page 12: Is there a typo in Eq. 2? Is the expression after "=" really Joule heating rate or just an assumption for current (as the term "(E + u_n x B)" is missing) ?

11.2 Author's response:

→ We thank the reviewer for pointing out this typo; this equation has been corrected in the revised manuscript (this is now equation 7)

→ We have also reshaped the whole subsection 3.3 "Measurement requirements", describing thoroughly the procedure of obtaining in-situ Joule heating. We also include formulas for ion-neutral collision frequencies and cross sections, which are parameters that Daedalus will also be able to estimate.

11.3 Author's changes in manuscript:

page 13, line 6 to page 16, line 9.

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Reviewer 1 Comment 12:

12.1 Comment from Reviewer:

The list of models on pages 13-14: Key references would valuable to add as the readers of GI may not be as familiar with these models as e.g. JGR readers would be.

12.2 Author's response and 12.3 Author's changes in manuscript:

–> References have been added in page 17, lines 16-24. These include:

TIE-GCM: Richmond et al., 1992; Richmond and Maute, 2014

GUMICS-4: Magnetic Field, Electric Field, Pedersen and Hall conductivities, Energetic particle precipitation Energy deposition, Joule heating, Field Aligned Currents (Janhunen et al., 2012)

IRI-07: Ne, Te, Ti, O+, O2+, NO+ (Bilitza and Reinisch, 2008, and references therein)

NRLMSISE-00: Tn, O, O2, Neutral density, Collision frequency (Picone et al., 2002, and references therein)

FMI - Alpha parameter: Pedersen to Hall conductivity ratio (Juusola et al., 2007)

HWM-07: Zonal neutral winds, Meridional neutral winds (Drob et al., 2008)

we have also included reference to the Weimer 2005 model of ionospheric potential

Weimer 2005: Ionospheric Electrostatic Potential (Weimer, 2005a, 2005b)

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Reviewer 1 Comment 13:

13.1 Comment from Reviewer:

Page 14, line 28: The mission with three year duration would cover all seasons and latitudes, but what would be the coverage in Magnetic Local time?

13.2 Author's response:

–> Indeed, Magnetic Local Time is more appropriate to demonstrate coverage of the

primary science objectives of Daedalus; we thank the reviewer for pointing this out. A coverage plot in terms of Magnetic Local Time has been added as Figure 11. In this figure, we have also included coverage plots for different inclinations, as the coverage is highly depended upon the selected inclination of the orbit. In addition, a plot of the latitude/altitude coverage of Daedalus has been added as Figure 15.

13.3 Author's changes in manuscript:

The following discussion has been added in the text:

Page 18, lines 33-34 and page 19, lines 1-6: "Based on the above orbital design, the coverage of Daedalus over the baseline lifetime of three years is shown in Fig. 11, in terms of Magnetic Local Time. As the coverage is highly dependent on the orbit inclination, simulations for several different inclinations were run: in the top panels coverage for an inclination of 80 degrees is shown; this simulation has an extensive coverage in terms of Local Time throughout the lifetime of the mission (3 yrs). In the middle panels coverage for an inclination of 83 degrees is shown, whereas in the lower panes coverage for an inclination of 87 degrees is shown, with a smaller resulting coverage in terms of Local Time. Thus the optimal inclination will need to be decided through a trade-off between the requirements for coverage of high latitudes vs. the requirements for Local Time coverage; this trade-off will be conducted in the definition phases of the Daedalus mission."

Page 31, lines 7-10: "The latitude and altitude coverage of Daedalus throughout its mission lifetime is presented in Fig. 15. As shown in this figure, Daedalus will focus primarily on high latitudes (>75o), where perigee will be lowered to 120km, but will also gather data at mid- and low-latitudes at its nominal perigee altitude of 150km."

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Reviewer 1 Comment 14:

14.1 Comment from Reviewer:

Page 22, line 30: A significant limitation in field-aligned current estimates by single satellites is the assumption of longitudinal gradients being insignificant when compared to latitudinal gradients. That limitation cannot be overcome by adding particle measurements if also they are provided by a single satellite. The magnetometer recordings by the lower pair of Swarm satellites have provided a solution for this problem. Probably also Daedalus with its mother-cubesat combination can tackle the problem similarly.

14.2 Author's response:

–> We agree with the comment of the reviewer, and we are aware of the limitation, that assumptions on the electric current geometry needs to be made by single satellite approaches, but also single satellite approaches have been proven to be very useful in investigating ionospheric currents, a prominent example is the CHAMP satellite. And that any information on currents is highly beneficial to the mission objectives. We have restructured the corresponding paragraph in the paper to reflect these limitations, and have added a number of corresponding references, as follows:

14.3 Author's changes in manuscript:

Page 26, lines 21-31: "High-precision measurements of in-situ magnetic fields are crucial for Joule heating estimates, for deriving current structures in the ionosphere and for studying and interpreting EPP fluxes and magnetosphere-ionosphere current systems. The Daedalus magnetometers will measure DC magnetic fields. DC magnetic field measurements are a required measurement in Eq. (1) and (4) of Joule heating and Eq. (5) of Pedersen conductivity; they are also needed for determining the pitch angles of precipitating charged particles, as measured by the EPDS. DC magnetic field measurements also allow for a quantitative determination of the upward and downward currents traversed by the instrument: there are well-established methods for extracting current measurements from in situ magnetometer data (e.g., Ritter and Lühr, 2006, Ganushkina et al., 2015), but they all rely on a priori assumptions about the structure of the currents. For example the horizontal cross-track component of the current is

assumed to be homogenous in the vicinity of the satellite. However, as it has been demonstrated in several earlier studies (e.g., Wang et al., 2006, Laundal et al., 2016, Zhou and Lühr, 2017) current estimates also from single satellite data are essential for the investigation of space environment. "

Laundal et al., 2016; Ritter and Luhr, (2006); Wang et al., 2006; Zhou and Luhr, 2016

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Reviewer 1 Comment 15:

15.1 Comment from Reviewer:

Page 23, line 24: The sentence "This expression has been proven to be accurate to better than 1%" is a strong statement and needs therefore also a reference. Does the statement hold for all frequencies? Does it assume something about ionospheric electron content variations?

15.2 Author's response:

–> This statement has been revised and clarified, and references are provided. The revised statement is as follows:

15.3 Author's changes in manuscript:

page 27, lines 15-18: "The refractive index of the ionosphere, n, is given by the Appleton and Hartree equation; taking into account that the electron gyro frequency is typically 1.5MHz, the plasma frequency rarely exceeds 20MHz, and the collision frequency is approximately 104 Hz, the refractive index of the ionosphere can be approximated as: n = 1 – 40.3 N / f 2 to an accuracy of better than 1% (Klobuchar,1996), where N is the electron density and f is the system operation, in Hz."

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Reviewer 1 Comment 16:

16.1 Comment from Reviewer:

Page 23, lines 27-28: The definition of TEC is confusing as it mentions vertical column and the path from satellite to receiver (which usually is not vertical) in the same sentence. Please, make clear distinction between Vertical TEC and Slant TEC.

16.2 Author's response:

–> The definition of TEC has been updated and a distinction between Vertical TEC and Slant TEC is provided in page 27, lines 11-14. Also references regarding GNSS-derived TEC products from past missions were added. The revised sentense is as follows:

16.3 Author's changes in manuscript:

Page 27, lines 24-30: "TEC is defined as the integral electron density in a one-square-meter cross section column along the signal transmission path. It is divided into two subcategories, vertical TEC (VTEC) and slant TEC (STEC). STEC is the TEC along the GNSS satellite-receiver line of sight, while VTEC is determined by integration of the electron density on a perpendicular to the ground standing route. Daedalus will provide STEC data, which can be translated during post-processing to equivalent VTEC. Regarding GNSS-derived TEC products, Daedalus will build on the heritage from SWARM (Park et al., 2017), CHAMP (Heise et al., 2002), GRACE and COSMIC (Alizadeh et al., 2011). The GNSS receiver will also be used for attitude knowledge."

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Reviewer 1 Comment 17:

17.1 Comment from Reviewer:

Page 28, line 15: Please explain low I_sp and high I_sp

17.2 Author's response

–> low I_sp and high I_sp are now explained in the text

17.3 Author's changes in manuscript:

–> The following paragraph has been added with respect to I_sp in page 34, lines 22-30:

"Maximizing the number of dipping maneuvers depends on the total mass of the propellant and also on the propellant's specific impulse (Isp): the latter is a measure of how efficiently a propulsion subsystem uses the propellant, with higher Isp meaning that less propellant mass is needed for a given thrust. In addition, the required time for achieving the desired altitude descent or ascent depends on the thrust capability of the thruster, with higher thrusts corresponding to faster maneuvers. In the presented simulations, a conservative specific impulse of 240s and a high-thrust propulsion system of 20N total thrust was assumed. Commonly, a lower thrust ($\sim$1N) system is also used for attitude purposes. One constraint regarding the selection of the propellant is that it should not contain constituents that could contaminate IMS and NMS measurements. Another way of addressing this constraint is to avoid firing the thrusters at the region of interest (perigee region), with the disadvantage of more fuel consumption, as apogee maintenance maneuvers off the perigee need more fuel."

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Reviewer 1 Comment 18:

18.1 Comment from Reviewer:

Page 33, line 12: I wonder why the authors want to highlight GIC as the most important societal relevant application of Daedalus. Is Daedalus really the best asset to gain understanding on processes causing high GIC values? I would rather pick the drag experienced by satellites and space debris as the core application area for Daedalus research. The drag business may not currently be the hottest topic in space weather discussions, but its importance is continuously growing.

18.2 Author's response:

–> We agree with this comment of the reviewer and have revised the manuscript accordingly. Accurate predictions of satellite drag are indeed of increasingly higher importance, and this has been emphasized in Section 5.1 On the Anticipated Impact of the Scientific Advances of Daedalus; furthermore GICs are no longer featured as the most important societal relevant application of Daedalus, and are moved to anticipated impact number [6].

18.3 Author's changes in manuscript:

Page 37, lines 18-23: "[3] . . .during geomagnetic storms and substorms, currents with increased amplitudes close through the LTI, producing enhanced Joule (ohmic) heating (Palmroth et al., 2005; Aikio et al., 2012) and leading to significant enhancements in neutral density, which in turn results in enhanced satellite drag. In particular, accurate estimates of drag experienced by satellites and space debris is increasingly becoming important with the continuously growing human activities in space. [4] Through its novel measurements, Daedalus will provide critical measurements for Joule heating estimates that can be used as anchor-points in global circulation models."

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Reviewer 1 Comment 19:

19.1 Comment from Reviewer:

Figure 7: I find particularly the MHD results interesting, since they cover also mid and low latitudes. I've understood that MHD approach is good particularly at high latitudes, where it captures the magnetosphere-ionosphere interactions nicely, but I have not seen previously MHD results on Joule heating for mid and low latitudes. These results would deserve some further explanation in the text.

19.2 Author's response:

→Thank you for this comment. The Joule heating within the mid latitudes comes simply from the fact that there is Pedersen conductivity and electric field within the modelling grids. The GUMICS modelling results in the mid latitudes are misleading in the sense that the results come just from the fact that the modelling parameters must be continuous over a sphere. The TIE-GCM modelling domain extends from -87.5° to + 87.5°, indicating that its results at the mid latitudes are in fact calculated.

19.3 Author's changes in manuscript:

–> We added the domains of calculation to the caption of (now) Fig. 6.

–> In the manuscript text, on Page 17, lines 6-8, we have added the following notion: "The GUMICS-4 modelling domain covers only the high latitudes, where the code is coupled to the magnetosphere, while the results on low and mid latitudes merely represent a continuity over a spherical ionospheric domain. This means that the results can be compared at high latitudes only."

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Reviewer 1 Comment 20:

20.1 Comment from Reviewer:

Figure 12: This figure is widely used to demonstrate the complexity of high latitude ionospheric currents. However, from the viewpoint of Daedalus the illustration is still too simple, because it describes ionospheric currents as two-dimensional sheet currents. In reality the currents do not flow in one sheet but in a three dimensional volume and there has been even some speculations on internal current closure inside the ionosphere (Amm et al, JGR, 2011). In favorable conditions Daedalus can contribute to such speculations in unprecedented ways by its mother-cubesat combination.

20.2 Author's response:

–> The Reviewer is absolutely right and we agree with this remark. However, as the

Figure is already rather busy, we cordially opt not to change the setup. Instead, we add the Reviewer's notion into the text, and add the reference.

20.3 Author's changes in manuscript:

On Page 30, lines 27-29, the text now says: "An overview of the observing scheme through the complex high-latitude current system is given in Fig. 13, which for illustrative purposes describes ionospheric currents as two-dimensional sheet currents, while in reality the currents are three-dimensional with existing speculation as to how the currents are closed (Amm et al., 2011)." Further below in the same paragraph we say: "Further, Daedalus can contribute to current closure speculations in unprecedented ways by its mother-cubesat combination."

Replies to Reviewer 2 Comments

We thank the second reviewer for his/her comments on the manuscript. We have significantly updated the paper with new figures, references and sections added, as described in the following:

Reviewer 2 Comment 1:

1.1 Comment from Reviewer:

Although the discussed research questions and mission challenges are highly interesting topics, the work has certain basic problems in terms of a research paper. In fact, one cannot avoid obtaining an impression that the text and material may be based on an instrument proposal, which spirit and goals are focused on selling the mission concept. A research paper should have a more analytical and quantitative compared to the current manuscript. -> Suggestion: Authors should make major improvements in the manuscript to build it up into a scientific paper. The apparent proposal behind the

manuscript is only a good starting material.

1.2 and 1.3 - Author's response and Author's changes in manuscript:

In response to the reviewer's comment, we have made the following changes to the paper:

–> The statements of Section 5.3 were removed, and Section (5.2), which includes Discussion and Conclusions, was rephrased with objective rhetoric that includes references to areas where Daedalus will have impact.

–> Statements made in the paper are supported by scientific literature and background is enhanced by providing and discussing a number of references, on Joule heating, Sub-satellite payloads, TEC, etc; in total, 33 new references have been added at various points in the paper.

–> The paper has been re-structured, removing figures that are not adding to the scientific justification, such as Figure 1 and Figure 15.

–> The scientific justification for the sub-satellites has been made more specific and is supported by literature and lists of potential instrumentation.

–> Figures 9, 10, 11, 15, 16, 17 18 have been added supporting the mission analysis

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Reviewer 2 Comment 2:

2.1 Comment from Reviewer:

Include proper references of earlier very important work: Aforementioned "proposal-research paper" dilemma arises in many places in the manuscript. For example, the science case is justified by introducing relatively old Joule heating studies. At the moment a reader cannot be sure have other previous MHD modelling studies like

- Slinker et al., Comparison of global MHD simulations with AMIE simulations for the events of May 19–20, JGR, 1996, https://doi.org/10.1029/1999JA900403 - Lopez et al., Coupling between the solar wind and the magnetosphere during strong driving: MHD Simulations: IEEE Transactions on Plasma Science August 2004, Vol. 32(4), pp.1439-1442 - Hernandez et al., Ionospheric joule heating during magnetic storms: MHD simulations, Advances in Space Research, 2005, Vol.36 (10), pp.1845-1848 and some of the most recent global modelling studies of the topic e.g. - Connor et al., et al. Modeling the ionosphere-thermosphere response to a ge- omagnetic storm using physics-based magnetospheric energy input: OpenGGCM- CTIM results, Journal of Space Weather and Space Climate; Vol. 6, (2016). DOI:10.1051/swsc/2016019) not been cited in order to make the science case more dramatic and attractive, or is it really so that not much has happened in the global modelling field in a decade?

-> Suggestion: Authors should include proper references of earlier important works and put the science case into a wider research context.

2.2 Author's response:

–> As also discussed in point 1 above, statements made throughout the paper are now supported by scientific literature and background is enhanced by providing and discussing a number of references, on Joule heating, Sub-satellite payloads, TEC, etc; in total, 33 new references have been added at various points in the paper. Related to other previous MHD modelling studies, the following paragraph has been added in Section 2.1.1:

2.3 Author's changes in manuscript:

Page 7, lines 19-29: "Estimates of Joule heating have also been based on empirical models such as the Assimilative Mapping of Ionospheric Electrodynamics (AMIE) procedure (Chun et al., 1999; Slinker et al., 1999), the Grand Unified Magnetosphere-Ionosphere Coupling Simulation (GUMICS-4) magnetohydrodynamic (MHD) model (Palmroth et al., 2004, 2005), the Lyon-Fedder-Mobarry (LFM) MHD model (Lopez et al., 2004; Hernandez et al., 2005; Slinker et al., 1999), the Compiled Empirical Joule

Heating (CEJH) empirical model (Zhang et al., 2005), the Open Global General Circulation Model (OpenCCCM) coupled with the Coupled Thermosphere Ionosphere Model (CTIM) and the Coupled Thermosphere-Ionosphere-Plasmasphere electrodynamics (CTIPe) model (Connor et al., 2016). Through such modelling the driving of Joule heating is believed to be well understood: in particular, MHD modelling has shown that Joule heating is controlled directly by the solar wind dynamic pressure (e.g., Lopez et al., 2004; Hernandez et al., 2005); however the quantification of Joule heating is a still unresolved issue, with great discrepancies between different modelling approaches."

Reviewer 2 Comment 3:

3.1 Comments from Reviewer:

Elaborate instrument and nanosatellites descriptions. There is no quantitative enough comparison between properties of the proposed instruments and the previous instruments neither instruments onboard forthcoming missions. The description of nanosatellites is also quite vague. At the moment, the idea of a mission consisting of a mothership and nanosatellites is not alone an innovative idea, but rather a standard starting point. The main question when nanosatellites are proposedto support the mission is how useful information, in practice and in reality, a nanosatel-lite can provide, taking into account its typically poor – and highly challenging – attitude control as well as its limited resources in terms of mass, energy, volume, telemetry etc. all of which cause strong limitations to nanosatellite's instrumentation. Furthermore, at the moment the paper does not state clearly what are the properties of the instruments onboard nanosatellites and how useful they can be.

-> Suggestions: Authors should strengthen the payload and nanosatellite descriptions in the manuscript as well as show more clearly how the payload is different from earlier and forthcoming missions.

3.2 Author's response:

–> Indeed, this part was not discussed in detail in the originally submitted paper, and both reviewers pointed this out. We have revisited this discussion, which is now greatly enhanced to include a justification of the scientific objectives of the sub-satellites, prioritization of the instruments and a detailed list in Table 3 of instruments that have flown or that are in a state of development. The following detailed discussion has been added in Section 4.2.9, "Sub-satellite Instrumentation" in response to the CubeSat instrument selection, status of development and prioritization:

3.3 Author's changes in manuscript:

"As discussed above in Section 3.3, Joule heating is expected to maximize in the altitude region around 120 km. As discussed in Section 4.1 of the Mission Orbital Design, the main Daedalus spacecraft will be able to estimate Joule heating by measuring E, B, un, Nn, Ne, Ni, and Te in-situ at these altitudes during the perigee descent campaigns. The main science objective of the deployed sub-satellites is to provide measurements that will enable (a) a differentiation between temporal and spatial effects of the measured parameters while both the main spacecraft and the sub-satellite are at 120 km; (b) a second point of measurements at 120 km while the main spacecraft ascends to higher altitudes, after the dipping campaign is competed, which will provide estimates of the vertical gradients of Joule heating, and (c) measurements below 120 as perigee decreases. In the following we discuss the prioritization of context measurements that can be provided by the sub-satellites, and a preliminary assessment of their feasibility. Out of the measurements that are required to obtain Joule heating, as discussed above analytically, the electric field at an altitude of 118 km can be about 20 mV/m (Kirkwood et al 1988), while above 200 km they can be in the order of 20-40 mV/m (Davies and Lester (1999). Electric fields vanish below the altitude region where σP maximizes. The exact profile of E between 140 km and the altitude of maximum σP is not known. Since the electric field is introduced into the JH equation as squared, it is expected to have a considerable impact if it is not measured properly at low altitudes. Thus E is a

key parameter to measure at a second point below the perigee altitudes of the main satellite, at altitudes of maximum σP. Neutral density, Nn, and neutral wind velocity, un vary significantly between the 140 km region and the region where σP maximizes (e.g., Cai et al., 2013); Nn affects the collision frequencies and un is directly related to qj. The consequences to the overall estimation of the Joule heating are thus also considered to be considerable. Electron density, Ne and ion density, Ni can reasonably assumed to be the same in this region. They can vary noticeably between the 140 km and altitudes of maximum σP (up to a factor of 2-5, based on TRANSCAR simulations; see, e.g., Blelly et al., 2005). Since these parameters go to the collision frequency estimation, which is also a function of Nn, their role can not be neglected, but maybe they are of secondary importance compared to E, Nn and un for Joule heating estimations. However, their role is significant as a proxy for EPP estimations, and simultaneous measurements of Ne at different altitudes along the same orbit (even with the implications of the phase difference between the two satellites, as described in Section 4.3.5 below) can provide significant improvements to current models that are used as proxy for EPP, such as the Rees et al. model, by improving the assumptions made therein (see, e.g., Schunk and Nagy, and Semeter and Kamalabadi, 2005). Furthermore, in-situ measurements of Ne would also be relevant for studying ionization and the energy input by solar EUV. For example, Lin and Chu (2017) recently performed an extensive modeling, but could only compare to the ~40 year old AE-C data, which reached down to 135 km. The combination of Ne from the main satellite at 150 km perigee and the sub-satellite at 120 km perigee would provide a novel dataset from which to improve such modeling. Finally, measurement of the magnetic field, B, is important for Joule heating estimations, but not critical, as models of the magnetic field at these altitudes are considered to have high fidelity. In the following we discuss the maturity of miniaturized instrumentation for the above parameters. The technology for nanosatellites based on the CubeSat paradigm is advancing at a very rapid speed. With much improved capabilities and reliability over the last decade has also followed the demonstration of the utility of CubeSat-based missions for a broad range of applications [see e.g. Zurbuchen et al., 2017]. Consolidation of the observational requirements will dictate the observational requirements also for the sub-satellites, and further analysis and prioritisation of the science questions will determine for which parameters the extended lower altitude coverage is most essential and can be supplied by a CubeSat. Currently, most, but not quite all, of the above listed parameters have well-proven instrument solutions. Based on currently demonstrated capabilities and new capabilities that are in advanced state of development, the feasibility of achieving measurements required for Daedalus from a CubeSat-based platform is summarized in Table 3, including a classification in terms of expected advancement by the time of Daedalus' launch, names of corresponding missions and references pointing to the status of development. In this table it can be seen that, in particular, measurements of Ne, Nn, Ti and composition of ion and neutral species, as well as measurements of the magnetic field all have proven, or well-advanced development solutions for miniaturized platforms, including CubeSats. Regarding Electric fields, an instrument based on the double-probe technique has been developed for a multi-satellite mission concept, and is likely to be demonstrated within the timeframe of the development of Daedalus (e.g., Crowley et al., 2015). Recent developments in the miniaturization of neutral wind instruments indicate that un measurements are also likely to be enabled onboard CubeSat platforms in the near future (Rod Heelis, personal communication, 2019). These measurements, therefore, constitute high-priority objectives that are considered to be feasible for the Daedalus CubeSats."

See Table 3 in the revised manuscript

Reviewer 2 Comment 4:

4.1 Comments from Reviewer:

Concretize the mission analysis. Comparison of the mission described in the paper to other missions lacks enough comprehensive quantitative analysis. There are several

highly “selling” superlatives and statements, which are acceptable – and also needed - in a proposal, but which requires detailed scientific justification in a research paper. There are also several bulleted lists of text and statements and overly short subsections, which do not fit smoothly to the manuscript. When the mission analysis is considered, an interested reader would appreciate, or even anticipate, to see even rough simulation results that show what kind of plasma and field parameters the mission could provide along the suggested orbits and how the parameters will be used to fulfill the science requirements, especially, to quantify Joule heating. Such a simulation should also include inaccuracies in the measured parameters caused by limitations of instruments. At the moment, it is questionable how inaccurate the values of Joule heating, which depends on numerous plasma and field parameters - which also should be measured simultaneously (Eqs. 1-4) – might be and, consequently, how accurate new quantitative information about Joule heating the mission really could provide. An interesting question, which is not addressed in the work, is how the instruments on the nanosatellites - especially their magnetometers- combined with more comprehensive instruments on the mothership can increase the science return. Especially, whatadvantages arise from different orbits and orbital evolution of the nanosatellites and the mothership.

-> Suggestion: Authors should provide more detailed mission analysis, especially, analyze more in-depth the impact of the payload on the scientific mission and the nanosatellites. The presentation style should be that of a research paper.

4.2 Author's response and Author's changes in manuscript:

–> Bulleted list in page 10, lines 5-11 has been removed

–>The impact of the sub-satellite payload on the scientific mission has been analyzed in Section 4.2.9, as described in response to the reviewer's comment Number 3

–> An extensive analysis has been added in Section 3.3 of the Measurement Requirements, which discusses and derives the scientific methodology that should be followed in order to resolve the approximations that are valid in order to meet the primary science objectives. This is described in detail in Eq. [1] through Eq. [23] in this section. In summary, it is concluded that, in order to measure all the parameters that go into Joule heating calculation in a local volume of space, the required measurements are: neutral winds, ion drifts (along track and cross-track), ion density, ion composition and ion temperature, electron temperature, neutral density, neutral composition (primarily N2, O, O2, N, NO) and neutral temperature, magnetic field and DC electric fields. The corresponding instrumentation is discussed in Section 4.2, which has been updated with a thorough analysis of the instrumentation onboard sub-satellites.

–> In support of the Measurement Requirements, references to rocket flight measurements of JH have been added in Section 2.1.1.

Reviewer 2 Comment 5:

5.1 Comment from Reviewer:

Improve figures. Another example of the “proposal type” material includes some of the figures. Especially, Figs. 1 and 15 are suitable figures for a presentation or for a proposal, but their information content is so low that it is highly questionable why such plots should be included into the paper.

-> Suggestion: Author should justify the importance of Figures 1 and 15.

Moreover, in many plots, units are not given and it is unclear from where the plots come from. A reader should be aware of whether the plot is a result of a new analysis – in this case the analysis should be described in detail - , or is it taken from some previous publications – in this case there should be a reference to the work. Moreover, font sizes are often too small and some lines are practically invisible.

-> Suggestion: Authors should check all figures and, for example, make sure that units and original sources of the plots are given clearly.

5.2 Author’s response and Author’s changes in manuscript:

–> At the recommendation of the reviewer, Figures 1 and 15 have been removed. Further changes and additions in terms of figures include the following: Figure 10 has been added, with Daedalus Apogee, Perigee and Perigee latitudes. Figure 11 has been added, with magnetic latitude vs. magnetic local time coverage of Daedalus. Figure 15 has been added, with a quantification of the altitude coverage. Figure 16 has been added, with a quantification of the latitudes of descent to lower perigee altitudes. Figure 18 has been added, with a quantification of the conjunctions between the main spacecraft and the sub-satellites in terms of the time difference between them when passing above the same latitude.

Reviewer 2 Comment 6:

6.1 Comment from Reviewer:

Make minor improvements. The paper includes several places requiring minor fine-tuning in order for the work to fulfill typical research paper standards. For example, acronyms are now presented but described only later, even several times, units are not given and figures miss information.

-> Suggestion: Authors should proofread the manuscript and add missing scientific details.

6.2 and 6.3 Author’s response:

–> The paper has undergone thorough proofreading; acronyms have been added, statements and scientific details have been supported by references as described above (33 new references in all), and units in figures have been reviewed.

Please also note the supplement to this comment:
https://www.geosci-instrum-method-data-syst-discuss.net/gi-2019-3/gi-2019-3-AC1-supplement.pdf

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Interactive comment on Geosci. Instrum. Method. Data Syst. Discuss., https://doi.org/10.5194/gi-2019-3, 2019.