The Ionospheric Connection Explorer Mission

Mission Goals and Design

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Abstract

The Ionospheric Connection Explorer, or ICON, is a NASA Explorer mission, developed and managed by the Space Sciences Laboratory at the University of California, Berkeley with key support from several partner institutions. ICON will explore the boundary between Earth and space to understand the physical connection between our world and our space environment. This connection is made in the ionosphere, which has long been known to respond to space weather driven by the sun, but it has been recognized in the 21st century that the energy and momentum of our own atmosphere regularly having effects of equal or greater magnitude. ICON's goal is to weigh the impacts of these two drivers as they exert change on our space environment. Here we describe the specific science objectives that fulfill this goal, as well as the means by which they will be achieved. The instruments selected, the overall performance requirements of the science payload and the operational requirements are also described. ICON's development began in 2013 and is on track for launch in 2017.

1. Introduction

The way in which planetary atmospheres interact with their space environments has emerged as a top science priority for NASA. (Jakosky et al., 2015; Bougher et al., 2015]). New focus and interest in this topic at Earth has originated in a number of recent and surprising discoveries that highlight the apparent influence of the troposphere and stratosphere on conditions well above the boundary of space (~100 km altitude at Earth), extending to the peak in the ionosphere (~ 300 km) (cf. Sagawa et al., 2005; Immel et al, 2006, 2009; England et al., 2006a, 2007; Hagan et al., 2007; Goncharenko et al., 2010). Global-scale imaging of the ionosphere afforded by a number of NASA and DoD missions has provided one of the keys to realizing this apparent connection. (Mende et al., 2000; Christensen et al., 2003)

Though the solar and solar wind inputs to this region (and geospace as a whole) are now well quantified, the potential drivers of ionospheric variability originating from the troposphere and stratosphere are not. ICON is a single spacecraft mission that measures and analyzes these drivers, combining for the first time remote optical imaging and *in situ* plasma measurements whose observations are tied together by Earth's magnetic field. In this way, ICON simultaneously retrieves all of the properties of the system that both influence and result from the dynamical and chemical coupling of the atmosphere and ionosphere. With this approach, ICON will be the first mission to separate out the variables and pinpoint the real cause of the variability. ICON will give us the ability to explain how energy and momentum from the lower atmosphere propagate into the space environment, and how these drivers set the stage for the extreme conditions of solar-driven magnetic storms.

ICON performs a scientific investigation that would nominally require two or more satellites, one sampling the conditions in the lower thermosphere that are magnetically connected to a second set of observations at the peak of the ionosphere. With the instruments of the payload carefully selected and designed to meet the scientific measurement needs, and the performance of the spacecraft designed to support all of the necessary science operations, ICON performs the work of two satellites with a straightforward mission operations concept. In fact, the mission design allows ICON to perform thousands of individual comparisons that would be infeasible to achieve with any multiple-satellite mission. With ample instrument and spacecraft performance margins, ICON fills a key science gap in the "great observatory" of Heliophysics missions, and provides an innovative design basis for future missions to investigate (electro)dynamical coupling processes in planetary atmospheres.

ICON is a small observatory, weighing approximately 290 kg, that can be placed into its circular 575 km altitude, 27° inclination orbit by the small Pegasus launch vehicle built by Orbital ATK. Once on orbit, ICON will continuously measure remotely the winds and temperatures of the upper atmosphere, and retrieve ion density profiles in the same region. It will also continuously measure the ion velocity vector at the observatory. The orbit selected provides ICON two key characteristics: 1) extensive periods of magnetically-connected remote and *in situ* measurements, 2) rapid orbital precession to sample all available ranges of latitude, longitude, and local time. Further, with a maneuver of the observatory, ICON has the capability to "image" winds of the upper atmosphere at both the northern and southern footpoints of the magnetic field line that reaches 575 km at its apex, providing a completely new view on ion-neutral coupling and dynamo electric fields in Earth's space environment. Here we describe key aspects of the mission design including the payload compliment and operational concept, given the science objectives described below.

2. ICON Science Objectives

ICON's science objectives are to understand: 1) the sources of strong ionospheric variability; 2) the transfer of energy and momentum from our atmosphere into space; and 3) how solar wind and magnetospheric effects modify the internally-driven atmosphere-space system. Here we discuss these objectives and what they drive in terms of specific measurements. The specific requirements for the mission in terms of scientific measurement precision, spatial resolution, sampling and revisit frequency are addressed thereafter for each objective in Section 3.

2.1 Science Objective 1: The source of strong ionospheric variability

Observations such as those shown in Figure 1 show that the electric field and associated F-region ion drifts in the ionosphere are highly variable under all geophysical conditions. This is plainly observed in equatorial region, where the ionosphere is most shielded from external (magnetospheric and solar wind) influences. The strongest candidates for the origin of this variability are the neutral wind and the ionospheric conductance. ICON measures the wind and ionospheric O^+ density at low-latitudes for comparison with the concurrently obtained electric field close to the magnetic equator to determine the source of this variability. To address Science Objective 1, the problem can be approached in two ways, either 1) A direct comparison of the magnetically connected neutral winds and ion drifts, or 2) A statistical comparison of the spatial characteristics (gradients, dominant scale-sizes, variances) of the magnetically connected neutral winds and ion drifts. ICON implements both of these studies.

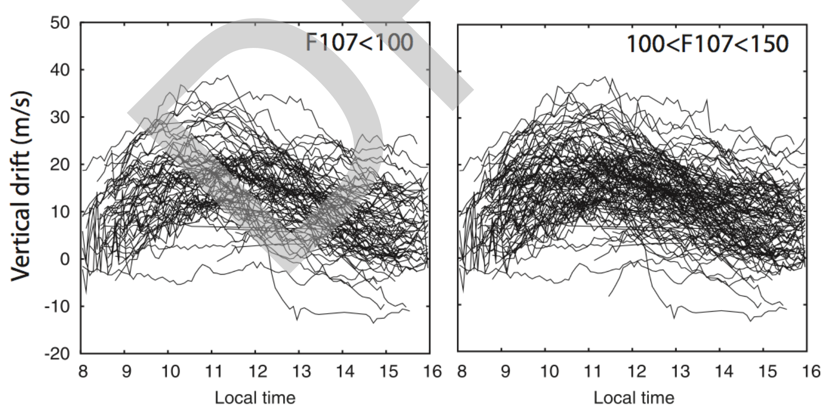


Figure 1 - Variations in the vertical plasma drifts measured at the magnetic equator during periods of low to moderate solar activity. After Alken et al. [2009].

To establish the source of the variability in the daytime F-region ion drifts near the magnetic equator, we require knowledge of: (1) the neutral winds that can create dynamo electric fields, throughout both the E- and F-regions (altitudes 100 – 300 km, above which winds are near-constant with altitude); (2) the Hall- and Pedersen-conductance throughout the same region; and (3) the F-region ion drifts close to the magnetic equator. For item (1), this requires observations of the altitude profiles of the winds, which can only be obtained via limb-viewing remote-sensing instruments. For item (2) the E-region conductance in the low-latitude, daytime region is dominated by photochemistry that can be modeled accurately and validated with daytime O^+ density retrievals and assimilative modeling, specifically using IDA4d (bust). For item (3), because magnetic field lines at F-region altitudes can be considered equipotentials, the electric field and associated ion drifts can be observed at any point along the same magnetic field line above the dynamo region (~300-800 km altitude). Thus, it is vital for ICON to observe the neutral wind over the altitude range of the dynamo region (~120-160 km) and ion drifts at F-region altitudes (~300-800 km) in such a way that the two measurements are made on the same magnetic field line, and within a time-range that is small compared to the characteristic time-scales of the variability shown in Figure 1. As these two volumes are ~1000-2000 km apart, and the winds can only be observed over this range using remote-sensing limb observations, this can only be achieved via a combination of *in situ* determination of the electric field at the spacecraft with the remote-sensing of the winds on the limb. ICON determines the electric field by measuring the local ion drift with an Ion Velocity Meter (IVM) instrument, which for F-region altitudes is a direct proxy for the E-field. For locations close to the geomagnetic equator, these geometric requirements are met as described in Figure 2.

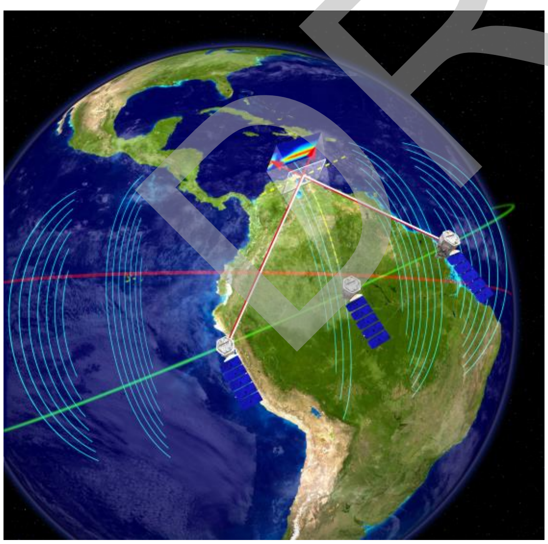


Figure 2 - The unique observational strategy of ICON is illustrated in a pass of the spacecraft where its combined measurements give a complete characterization of the dynamical coupling between the daytime ionosphere and thermosphere. The three locations of the illustrated spacecraft indicate steps in the orbit over a total of ~7 minutes.

Uniquely in this region, the geomagnetic field line curves down away from the spacecraft with a radius of curvature approximately equal to half the radius of the Earth, which follows the tangent points on the limb of the wind observations made at 45° and 135° to the spacecraft orbital track (necessary to provide vector wind measurements). This figure thus describes the required viewing geometry obtained within a few degrees (~10°) of the geomagnetic equator. As long as all measurements are made, a view either north or south from the observatory will meet this viewing geometry requirement. The IVM instrument needs to be ram-facing to make this measurement, but as it noted later, ICON carries two IVM heads separated by 180°, supporting complete scientific measurements for both north and south facing views.

2.2 Science Objective 2: How do large-scale atmospheric waves control the ionosphere at low latitudes?

Summary:

It is now understood that large-scale waves generated in the lower and middle atmosphere may propagate upward and into the upper mesosphere and lower thermosphere (MLT). In the MLT, such waves are the dominant source of wave energy, though expected to dissipate at altitudes above ~140 km. Corresponding wave structures in the plasma have been observed throughout the low-latitude ionosphere reaching up to heights of 800 km (Hartman and Heelis, 2007). One of the clearest examples of this is shown in Figure 3, where there is a close correspondence between tidal signatures at 115 km and ionospheric densities 100s of km higher. ICON will resolve fundamental questions about the coupling mechanisms between these two regions that drive similar-scale wave patterns and quantify the relative importance of (1) changes in the wind-driven electrodynamics; (2) changes in the conductance; (3) changes in neutral composition; and (4) direct forcing of the ionosphere by those large-scale atmospheric waves that actually propagate to higher altitudes. To do this, ICON must measure (1) the physical parameters that are directly associated with atmospheric waves: neutral winds, temperature, density, and composition, all as a function of altitude, local time and geographic location; (2) ion drifts on field lines co-located with (1); and (3) ionospheric density profiles, with coverage to match (1) and (2).

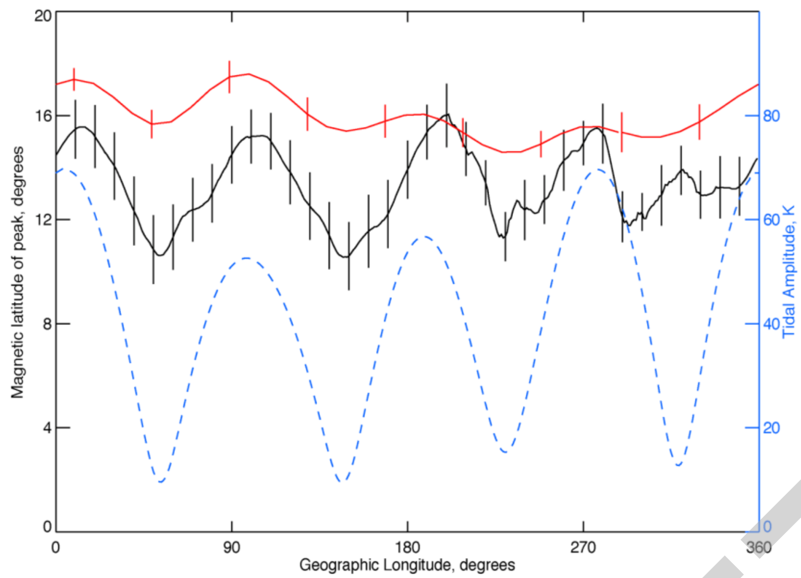


Figure 3 - Longitudinal variations in the nighttime FUV brightness of the EIA compared to the amplitude of predicted temperature variations driven by non-migrating diurnal tides at the equator. The FUV emissions originate from the F-layer of the ionosphere above 300 km, while the temperature amplitudes from the Global Scale Wave Model are shown at 115 km. After Immel et al., 2006.

Exciting results from recent work have shown a striking resemblance between the large-scale structure of the equatorial ionosphere and tides in the lower thermosphere. Solar thermal tides (as distinct from lunar gravitational tides) are atmospheric oscillations with periods that are sub-harmonics of a solar day. They are forced by processes connected with the diurnal cycle of heat release in the lower atmosphere. The daytime heating of Earth's surface by sunlight, absorption of solar radiation by ozone, and the release of heat in the condensation of water vapor in convective clouds are the major drivers of tides. Migrating tides are westward propagating waves which follow the apparent motion of the sun [Forbes, 1995]. Thus they are typically linked to the diurnal cycle of radiative heating by, for example, ozone in the stratosphere. By contrast, nonmigrating tides are linked with latent heat release from deep tropical convection which is preferentially associated with specific geographic regions, but which also varies diurnally. These oscillations propagate up from the lower atmosphere to the thermosphere where they drive large wave patterns in the winds, temperatures and composition.

Through these changes, it is believed that these waves are able to drive the motion, production and evolution of the ionosphere at low-latitudes, creating a coupling between our tropospheric weather system and the upper atmosphere and near-space environment that is stronger than ever previously known. Following the seminal paper by Immel *et al.* [2006], a number of recent studies have observed what appears to be tidally induced variability in the ionosphere and thermosphere: total electron content [Lin *et al.*, 2007], vertical ion drifts [Hartman and Heelis, 2007; Kil *et al.*, 2007], neutral winds throughout the thermosphere [Lühr *et al.*, 2007; Talaat and Lieberman 2010], thermospheric O/N2 [Zhang *et al.*, 2010], and ionospheric electrojet currents [England *et al.*, 2006]. Each of these studies has identified a possible mechanism or pathway to producing the effect. However, it is simply not known how the wave signature in the atmosphere is impressed upon the ionosphere.

A study by England *et al.* [2010] examined four of the proposed pathways described above. At present, we do not have sufficient data to rule out any of these four, or to determine how much of the longitudinal variability in the ionosphere can be attributed to each one of these. The only way to evaluate the competing influences is to simultaneously observe the key, unique features associated with each of these pathways along with the resultant ionospheric structure. In particular, these observations must be in the sparsely sampled 110-300 km altitude region where the coupling mechanisms are believed to operate most effectively. ICON will provide the necessary measurements of winds at E- and F-region altitudes, conductivity, and chemical composition that will resolve outstanding questions. Since each of the main tides in the thermosphere peak at different times of year, it is important that such observations be made at an appropriate cadence and duration to resolve the dominant mechanism. ICON provides the measurements and coupled models necessary to carry out exactly such a study.

Central to ICON's ability to address Science Objective 2 are its observations of atmospheric tides. Atmospheric tides are global-scale atmospheric waves with periods of 8, 12 and 24 hours, typical vertical wavelengths ≥20 km in the lower thermosphere (increasing with altitude to be quasi-infinite in the upper thermosphere) and horizontal wavelengths of integer fractions of the circumference of the planet (of order 60-360° in longitude and 30-90° in latitude). While the amplitudes of these waves can vary with season, previous observations of these waves in the mesosphere and lower thermosphere have shown that the dominant tidal waves persist for several months at a time.

2.3 Science Objective 3: How do ion-neutral coupling processes respond to increases in solar forcing and geomagnetic activity?

Remarkable changes in the ionosphere and thermosphere occur at low latitudes in response to disturbances in the solar wind. The electric field induced by the solar wind directly competes with internal drivers (Science Questions 1 and 2) and dynamo fields driven by storm-time neutral winds. Without comprehensive measurements of all the local drivers and the response of the ionosphere/thermosphere system, we depend upon numerical models to best understand the effects of these competing processes. ICON will provide the set of measurements that will allow for the first time a complete separation of internal "wind/wave-dominated" forcing from external "storm-driven" disturbance processes to understand how these processes interact to form the response of our ionosphere to storm inputs.

During periods of low magnetic activity, tidal forcing and other wave effects routinely shape the ionosphere (see Science Objectives 1 and 2). However, at enhanced levels of solar and geomagnetic activity the ionosphere changes on a global scale under the influence of EUV flare inputs [Immel *et al.*, 2003; Sojka et al., 2013], storm-time electric fields [Tsurutani et al, 2004], and global modification of thermospheric neutral wind and composition [Fuller-Rowell et al., 1991; Immel *et al.*, 2001]. ICON will be launched in the declining phase of solar activity, and will observe the I-T system affected by these inputs with a range of intensities. It will observe the modification of the equatorial ionosphere as it evolves from wave-dominated to storm-driven, a transition that is surprisingly complex and poorly understood, largely due to the absence of coordinated, simultaneous measurements such as those that will be made by ICON.

With the arrival of a disturbed solar wind, penetrating electric fields lift the ionospheric plasma across the dayside [Kelley *et al.*, 2010]. These effects decline as shielding by inner magnetospheric current systems becomes more effective, a process that can take an hour for low- moderate activity (Kp~3) [Earle and Kelley, 1987] or longer for more energetic events [Huang *et al.,* 2010]. The elevation of the F-layer significantly reduces ion-drag, an effect that models predict will allow F-region neutral winds to increase across the dayside [Fuller-Rowell *et al.*, 2002]. This buildup of momentum in neutral winds should be manifest at all local times thus modifying the dynamo action of the F-region that is most effective at night [Heelis, 2004]. At the same time, the F-layer is enhanced for the uplift reduces chemical recombination. When the denser layer does settle, ion-drag on the neutral winds exceeds the initial condition. Thus, a "simple" action near noon drives a complex system with feedbacks that must be quantified before the non-linear ionospheric response to external forcing can be understood and predicted. ICON will monitor all aspects of these processes as the geomagnetic storm progresses.

Furthermore, with prolonged activity, the high-latitude effects of the solar wind disturbance drive a temporary neutral wind dynamo at lower latitudes that builds a dusk-to-dawn electric field that usually opposes the normal dynamo field [Blanc and Richmond, 1980]. These types of electric field disturbances extend from high- to low-latitudes over the hours of the disturbance epoch. ICON will be the first mission to simultaneously measure both disturbance electric fields and neutral winds and their effects on the densest plasma in geospace, the low-latitude ionosphere.

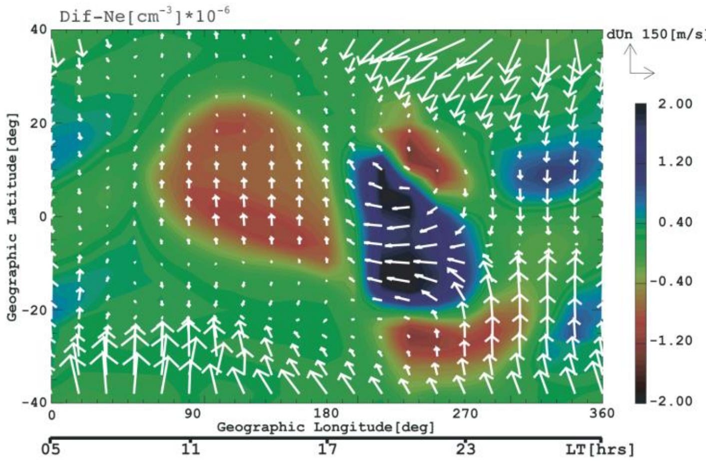


Figure 4 - Vectors show the difference in wind direction at 400 km altitude between a quiet and active run of a global I-T model from Maruyama et al. [2005], where colors indicate changes in TEC. Post-sunset zonal winds are highly reduced from their normal eastward flow. Is this due to ion-drag from the lowered F-layer or to disturbance winds from high latitudes?

Extensive modeling of the coupled behavior of the ionized and neutral gases has provided significant insight into the processes at work [e.g., Maruyama *et al.*, 2007]. The competing effects of penetrating electric fields and the disturbance dynamo have been evaluated using models, the latter of which, for instance, reduces zonal winds after the terminator (see Figure 4). However, recent results from incoherent scatter radars show that penetrating fields may actually reduce F-layer heights in this sector and therefore also slow zonal flow through increased ion drag [Kelley *et al.*, 1989]. Direct observations of F-region winds and ionospheric heights in this region are required to unravel the relative importance of these competing effects. Furthermore, any effort to quantify these effects must properly account for the strong tidal and wave-forced “internal” variability that could otherwise be mistaken as temporal variability introduced by external agents.

The spatial, temporal and precision requirements for measurements of neutral winds and composition, plasma density and velocity taken to meet Science Objectives 1 and 2, are also stringent enough to characterize geomagnetic storm effects. In meeting Objectives 1 and 2, ICON will obtain the baseline characterization of the internally driven non-linear coupling between these neutral and ionospheric parameters that will be used to validate the ion-neutral physics simulated in the coupled ICON numerical models. During periods of enhanced solar and geomagnetic activity, ICON will determine how these parameters deviate from their baseline and will relate them to the strength of the solar-wind electric field forcing that is externally applied to the global ionosphere-magnetosphere system. For characterization of the external forcing will be derived from the AMIE assimilative model, which can provide a robust measurement of the geo-effective cross-polar-cap potential (among other key parameters) through assimilation of ground-based data, aided by direct measurements of the solar wind velocity and IMF or radar data (as available). By comparing the temporal behavior of the disturbance-driven components of the low latitude thermospheric and ionospheric responses with the development of the CPP we will determine the relative importance of the drivers during different phases of increased geomagnetic activity.

3. Science Requirements

The ICON science requirements are developed such that the observatory may successfully achieve the scientific objectives described in the previous section. In the development of the requirements, the state of knowledge of the ionosphere-thermosphere system is reviewed, and the type and precision of measurements needed to fully address the objective is established. Through addressing the common needs of the three objectives, ICON's requirements are reduced to a set that meets all science demands.

3.1 Requirements for Science Objective 1

To establish the source of the variability in the daytime F-region ion drifts near the magnetic equator, we require knowledge of: (1) the neutral winds that can create dynamo electric fields, throughout both the E- and F-regions (altitudes 100 – 300 km, above which winds are constant with altitude); (2) the altitude profile of conductivity throughout the same region; and (3) the F-region ion drifts close to the magnetic equator. To provide sampling over the altitude range required, (1) and (2) can only be obtained via remote sensing, whereas (3) can be obtained *in situ* from LEO. These measurements can be compared scientifically in the geometric configurations described in Section 2.1.

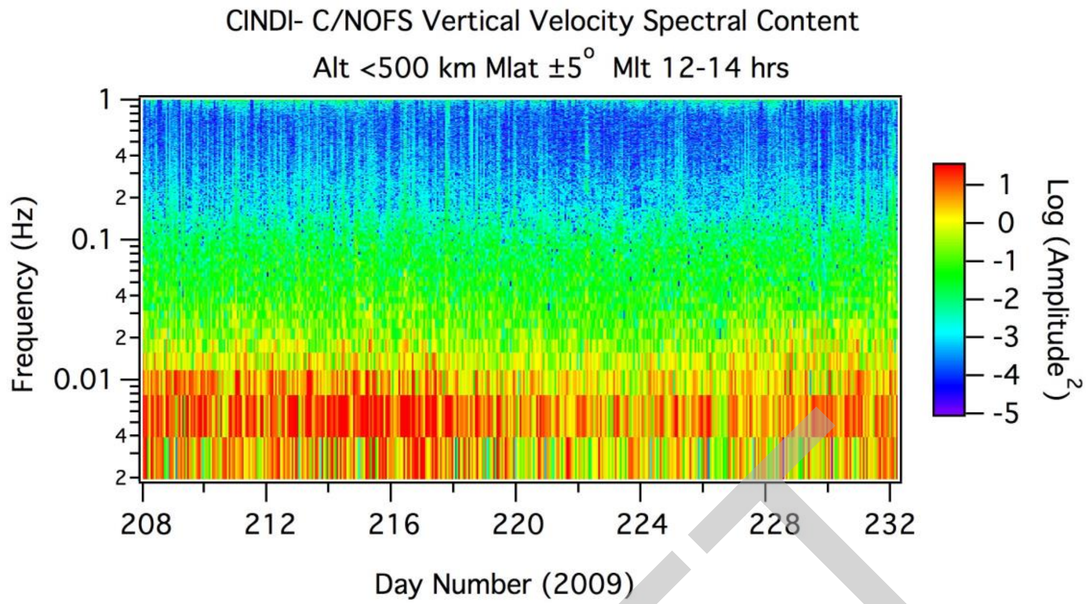


Figure 5 – Characteristic scale sizes in the vertical drifts measured by C/NOFS-CINDI close to local noon, magnetic equator. Power spectrum for 1 month of data is shown. Almost all the power in the spectrum is for variations with horizontal scale sizes over 800 km, thus ICON is designed to observe the variability of the drivers chiefly this scale and larger.

Figure 5 shows a survey of one month of data from C/NOFS CINDI showing the typical variability seen in the daytime ion drifts during quiet periods. While the instrument is sampling at scales down to one km in-track, the strongest variability is seen at scales of 1000 km or more (note, this is quite different from the scales of instabilities that can dominate such a spectrum at night). Thus, to establish the origin of this variability, ICON must sample the parameters in (1) and (2) at horizontal scales of 500 km, while measuring the related (3) at this resolution or better. These scientific measurement requirements define the instrument requirements regarding temporal and spatial resolution.

Typical wind speeds in the thermosphere are 50-100 ms^{-1}, so to determine if these produce the variability in the ion drift, ICON must measure winds with a per-sample precision better than 20 ms^{-1}. To determine if variations in the conductivity are able to produce the observed variability in the ion drift, ICON must measure the electron densities with a precision of 10 %. The related conductivity profiles are then determined using the IDA4D [Bust et al., 2004]. The variability in the ion drifts is often comparable with the maximum value of the drift, which can range in quiet times over -30 to +30 ms^{-1}. Precision of 10 ms^{-1}per sample of the plasma motion is needed to make comparisons with the winds and conductivity products, with spatial resolution at least twice that of the wind and conductivity measurements. These requirements drive aspects of the observatory fine pointing capability, many aspects of the instrument design, and for the remote sensing instruments, the performance of the retrieval algorithms.

The daytime E-region wind dynamo is the target for these measurements, specifically in those regions magnetically connected to the higher altitude plasma observations. The winds in the E-region, from 110-180 km altitude, can be expected to change rather rapidly with altitude. However, this assertion is based upon nighttime wind observations, and there are in fact very little on daytime winds in this altitude region. Though the nighttime E-region exhibits wind shears with reversals on scales of a few km, this is in the absence of strong drag from the daytime E-region plasma. Further, the dynamo fields originate in the convolution of those winds with a conductivity profile that varies more regularly with altitude (Heelis et al., Richmond et al.). In light of these facts, wind measurements with height resolution of 10 km obtained simultaneously over a range of altitudes through the daytime dynamo region will provide a great advance over any previous effort. Conductivity profiles should be determined on these scales as well. These requirements drive the spatial resolution of the remote sensing wind instrument, and the performance of the wind retrieval.

3.2 Requirements for Science Objective 2

To measure large-scale atmospheric waves and tides and their effects on the ionosphere, ICON must measure (1) the physical parameters that are directly associated with atmospheric waves: neutral winds, temperature, density, and composition, all as a function of altitude, local time and geographic location; (2) ion drifts on field lines co-located with (1); and (3) ionospheric density profiles, with coverage to match (1) and (2).

The most important observations are those of atmospheric tides in the neutral atmosphere. These waves have typical vertical wavelengths ≥20 km in the lower thermosphere (increasing with altitude to be quasi-infinite in the upper thermosphere) and horizontal wavelengths of order 1,000s km. The resolution of the observations in (1) must be a fraction of these wavelengths (1000 km is adequate, 500 km is ideal). Each of these parameters must be measured with sufficient sensitivity to capture the tidal perturbations of the atmosphere. Previous observations of tides in the region 90–105 km altitude allow us to specify the measurement precision required to observe waves of typical amplitudes.

Prior to discussing the specific measurement needs, it is important to consider the competing needs to provide good characterization of the tides at low to middle latitudes while maintaining the highest precession rate possible for rapid sampling of all combinations of latitude, longitude, and local time. Precession rate drops with increasing inclination, but the range of sampling is of key importance as well. For example, an equatorial (0^{o} inclination) mission could only provide the most limited information on tides, given the single latitude of observations.

An investigation of atmospheric tides and their effects at low-latitudes can be achieved from a range of orbital inclinations. The 27^{o} orbital inclination as described earlier for Objective 1 falls in this range, as described in the companion paper (England et al., this issue). This inclination provides access to a required range of latitudes and is sufficiently low to provide the rapid precession rate required for sampling all locations and local times within one month (27-day half-precession @ 575 km circular orbit). Tidal parameters will be obtained from the ICON observations using Hough Mode Extensions (HME; Forbes and Hagan, 1982). ICON will provide winds and temperatures from a latitudinal range sufficient to fully characterize the tidal components up to 400 km altitude for investigations of direct forcing of the F-layer, fully specifying tides that are critical to measure for equatorial science in less than half the time of the progenitor mission TIMED (with an ~60-day half-precession period).

Typical tidal amplitudes in the region of interest are of order 10 ms^{-1} and 20 K. Considering their wavelength, discussed above, winds and temperatures should be sampled with height resolution of 5 km. Further, because the tidal analysis is done over all data in these 54-days simultaneously, an analysis is considered with representative 5°×5°×1 hour LT bins, where multiple samples in each bin reduces the uncertainty in the wind and temperature to be fitted. Our orbit provides a minimum of 12 samples per bin for the winds and 24 for the temperatures. At each latitude, spatial-temporal fits are then made over all LT and longitudes (e.g. in the case of the wind, this fit involves ~5,000 samples). Thus, to achieve the 5 ms^{-1} and 5 K requirement in measuring the tides over 54 days, the instrument must measure with a precision of 17 ms^{-1} and 22 K per sample. Because the derived quantities are wave properties, rather than the absolute wind and temperature structure, there is no requirement for absolute accuracy beyond that the zero-wind determination cannot drift more than 2 ms^{-1} in any 54-day window. For smaller spatial bins of 5°×5°, the requirements are more stringent, with a precision of 8.7 ms^{-1} and 12 K per sample.

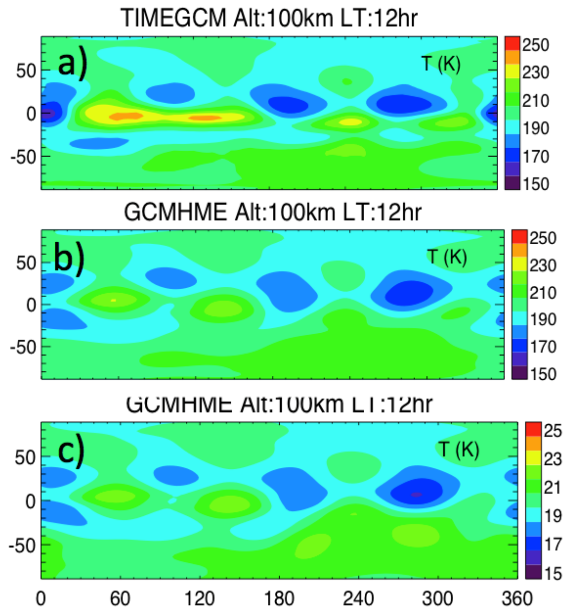


Figure 6 - Observing System Simulation Experiment of HME fitting routine to retrieve tidal components of the temperature field at the local time of noon. The temperature at the noon meridian at 100 km altitude predicted by the TIMEGCM for a 24-hour period is shown in Figure 6a. 100 km temperatures based upon a global HME reconstruction informed by both wind and temperature measurements using global sampling in the 90-105 km altitude range is shown in Figure 6b. The HME fit constrained only by data in the -12 to +42 degree latitude range (simulating ICON's orbit and views) is shown in Figure 6c. This demonstrates a case where the HME fits constrained to data from the ICON orbit are highly similar to the fit to a complete global specification. Thus in this case the ICON orbit demonstrably meets the requirement for precise reconstruction of the HME from observations.

It is worth noting that throughout the discussion of the requirements for Science Objective 2, the requirement is stated in geophysical units, averaged over a spatial-temporal bin of a particular size. This is only used as a means of translating the requirement from the science objective to the instrument measurement requirements. No actual binning is used in the actual scientific analysis (the full spatial and temporal resolution available are used) and as such the size of the bin stated is of no consequence other than in helping translate the science requirement (e.g. the tidal spectrum from 60-days of observations) into a per-measurement instrument requirement. The performance of HME fitting routines that are constrained by data in the ICON sampling range is shown in Figure 6. In comparison to HMEs that are constrained by a complete global set of observations, the fits to the limited range of data are, in this example, realistic. A broader set of tests is performed in the companion paper to this report [Forbes et al.; England et al.; this issue]

To quantify further effects of tidal forcing, two parameters are measured: (1) the neutral composition changes that tides induce [Roble and Shepherd, 1997] and (2) the vertical ion drifts they impose by their modulation of the E-region dynamo [Hagan *et al.*, 2007; Kil *et al.*, 2007]. The composition changes (O/N_2) are measured during the day where their importance to the ionospheric production rate is greatest. The tides studied have been reported to produce changes in O/N2 of order 10%, thus our requirement is to measure this ratio to 5% per 27 days (17(8.7)% per 1000(500) km sample as above). Vertical ion drifts are measured during day and night to study both electrodynamic and direct forcing of the ionosphere by tides. Previous observations have shown this varies by around 10-20 ms^{-1} in response to tides, so our measurement requirement is a precision of 10 ms^{-1} on scales of 500 km, or 7.1 ms^{-1} on scales of 1000 km.). Note that there is a more strict requirement on vertical plasma drift from Objective 1, which will supersede this requirement.

The time-integrated effects of photochemical and electric-field forcing on ionospheric densities must be directly measured in the ionosphere. Altitude information is critical to observe the coupling between different layers and the development of these signatures throughout day and night. The key ionospheric parameters, hmF2 and NmF2, can be retrieved from altitude profiles of dayside extreme-ultraviolet (EUV) 83.4 nm and nightside far-ultraviolet (FUV) 135.6-nm emissions. Previous observations have shown that tides produce typical changes in hmF2 of 40 km and NmF2 of 40%. These measurements must have height resolution of 20 km and sensitivity to retrieve NmF2 to 10%.

Modeling efforts using both SAMI3 and TIEGCM allow us to achieve closure on the relative importance of winds, electric fields and changes in neutral composition on changing ion density. The HMEs will be input to the TIEGCM (coupled to SAMI3) as a lower boundary condition. ICON observations throughout the low-latitude thermosphere-ionosphere system are used as a ground truth for these model outputs and to refine the model simulations. The model outputs, including non-observable parameters such as total neutral-ion momentum transfer are used to resolve the relative importance of the drivers.

3.3 Requirements for Science Objective 3

To evaluate the coupled behavior of the I-T system during periods of enhanced solar and geomagnetic activity, ICON will operate with a high operational efficiency to make continuous observations of conditions during which Kp rises to values of 5 or more. With our launch planned for June 2017, it is expected that ICON will encounter ~6–8 such events in its first 12 months of operations which is enough to establish the change in the underlying ion-neutral coupling during these periods. The effects of these events last for ~3-24 hours, so rapid sampling of all local times (total LT coverage in 1.5 hours) is required.

Objective 3 will be addressed using simulations from the TIEGCM/SAMI3 models that are both constrained by and compared to ICON's observations. These models are constrained at their lower boundary by the atmospheric tides ICON will measure (as addressed by meeting Objective 2) and at high latitudes using the AMIE assimilative model. AMIE produces high latitude potential maps that are constrained using all available data sources such as ground-based magnetometer networks, radars and solar wind monitors when available. Solar wind measurements are expected to be continuous during the ICON mission, with new assets committed to providing these [ref DSCOVR]. The TIEGCM/ SAMI3 models require AMIE output at 5-minute cadence, which will be produced for the entire ICON mission and provided as a mission data product.

To observe the motion of the F-layer in response to external forcing, ICON must measure (1) the low-latitude $\boldsymbol{E}\times\boldsymbol{B}$ ion drifts and (2) the height of the F-layer (hmF2) both day and night. Typical storm-time changes in the ion drifts are shown in Figure 7. ICON must measure these with a precision of 10 ms^{-1} in order to identify their perturbation from quiet times. For changes in hmF2 to have any impact on the neutral winds, they must be on the order of a neutral scale height (~40 km in this region), so these must be measured with a precision of 20 km. To separate the effects of photochemistry from transport in changing the F-layer, ICON must also measure (3) the neutral composition (O/N_2) during the day when ions are produced. Perturbations in O/N_2 must be larger than those produced by atmospheric tides to produce any noticeable effect. Finally, to observe the changes in the winds from the reduced ion drag or disturbance winds, ICON must measure the horizontal neutral winds at F-region altitudes in both daytime and at night.

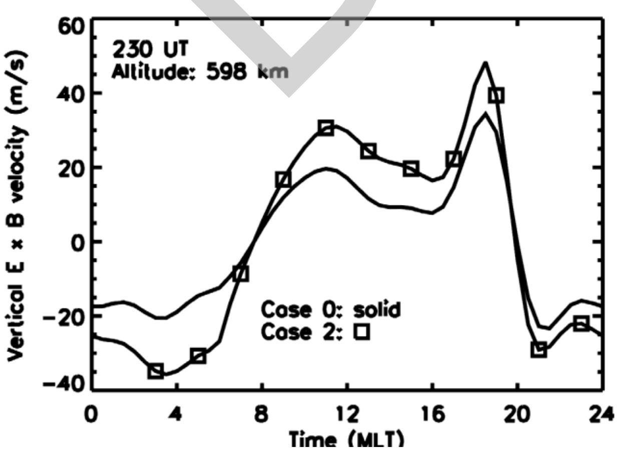


Figure 7 - Mean vertical drift as a function of local time under quiet and disturbed electric field inputs prescribed by the Rice Convection Model [Wolf and Kamide, 1983], after Huba et al. [2005]. The pre-noon maximum in upward drift corresponds to a peak in plasma production, while the 18 MLT peak is the pre-reversal enhancement. Recent measurements [Kelley et al., 2010] suggest more complex responses, such as where pre-reversal enhancement drifts may be reduced or even turn negative while the daytime drifts remain upward during active times.

Figure 4 shows the typical wind perturbations expected, which would be well represented if ICON measured the winds with a precision of 10 ms^{-1} in the F-region. For this objective, all requirements are in terms of precision. There is no accuracy requirement, as the absolute value of any parameter at any one time is not sought, but rather simply its change in relation to changes in geomagnetic activity.

Advances can be achieved by comparing the TIEGCM/SAMI3 models with the ICON observations. Specific conditions and behaviors of the system during each storm period can be evaluated, and attributed to aspects of the larger-scale/global storm response. Departures from modeled parameters can be evaluated in terms of the phenomena present regionally (e.g., pre reversal enhancement, daytime "superfountain"). Modifications of the free model parameters (e.g. eddy diffusion) can be tested if needed, offering a potential pathway for model improvements. Analyzing these final model runs with equivalent quiet-time simulations will enable us to identify departures in the I-T system associated with enhanced solar wind and geomagnetic activity. These simulations, combined with the capabilities necessary to address Objectives 1 and 2, fully describe the data and analysis required to also address Objective 3.

3.4 Science Requirements Summary

The science requirements discussed above were collected and held by NASA as mission-defining Level 1 requirements. Table 1 summarizes these measurement precision requirements (last column), and also reports the Level 2 (L2) requirement that the ICON project systems and instrument teams worked to meet during design and development phases of the mission, and verify before delivery. Losses from L2 performance are therefore acceptable, but avoided if possible to retain instrument performance margin to meet mission science goals during the 2-year science mission and beyond.

Program Level (L1) Science Requirements for ICON

Label	Science Requirement Statement	day/ night	Altitude (km)	Vertical Res.	Precision L1/L2
SR-1	ICON shall determine **altitude profiles of upper atmospheric wind vectors** on the limb with a horizontal range resolution of 500 km great circle.	Day/ Night	95-280/ 95-105 and 220-280	5-30 km/ 5 km and 30 km	16.6 ms^{-1} / 8.7 ms^{-1}
SR-2	ICON shall provide a measure of the **vertical ion drift** velocity component perpendicular to the magnetic field with horizontal range resolution of 250 km great circle.	Day and Night	*In situ*		10 ms^{-1} (and accuracy)/ 6 ms^{-1}
SR-3	ICON shall measure the **peak ion density of the daytime** and **nighttime** ionospheric F-layer with horizontal range resolution of 500 km great circle.	Day and Night	@ F-layer peak		33% / 10%
	ICON shall measure the **altitude of the layer peak** with horizontal range resolution of 500 km great circle.		N/A		±20 km / ±10 km
SR-4	ICON shall determine **altitude profiles of upper atmospheric temperature** at a horizontal resolution element size of 5°x 5° lat-lon	Day and Night	90-105	5 km	23.4 K / 12.2K
SR-5	ICON shall measure the **altitude profiles of O and N_2** to determine the column ratio of O/N_2 in the daytime thermosphere with horizontal range resolution of 500 km great circle.	Day	130-200 km column		16.6% / 8.7%
SR-6	ICON shall assimilate ionospheric measurements for determination of conductivity profiles coincident with limb measurements with horizontal range resolution of 500 km great circle.	Day	E- and F-Regions of ionosphere		10%
SR-7	ICON shall use geophysical models (e.g. HME, TIE-GCM, SAMI3, AMIE) to support recovery and determination of the following parameters: Atmospheric Tidal Amplitude and Phases, Coupled Ionosphere-Thermosphere parameters, and High latitude Potential Distribution.	Day and Night	E- and F-Regions of ionosphere		No Specification

Table 1 Science requirements for the ICON mission. The ICON baseline mission meets all of these requirements. The threshold mission is enabled by meeting requirements SR-1,2, and 6. At launch, the ICON observatory has the capability to meet the baseline mission and Science Requirements SR-1 through SR-5, and the Science Operations Center is prepared to generate products identified in SR-6 and SR-7.

Section 4. Science Instruments

4.1 Michelson Interferometer for Global High-resolution Thermospheric Imaging (MIGHTI)

The MIGHTI instrument is supplied by the Naval Research Laboratory (NRL). It can measure the wind velocity and atmospheric temperature in the ionosphere. Wind speed is measured by the Doppler shift of the atomic oxygen red and green lines (630.0nm and 557.7nm). Temperature is measured from the spectral shape of the molecular oxygen band at 762nm. The two arms of the MIGHTI, MTA and MTB are mounted orthogonally and image the upper thermosphere and provide the Doppler shift vector. A common Camera Electronics package, MTE, supports the cooled CCD imager used in each MTA and MTB. A Calibration Lamp, MTC, provides an optical calibration signal to both MTA and MTB via a fiber optic connection. Finally, a Stepper Driver, provided by UCB, is included on each MIGHTI optical assembly. It provides an electrical interface between the MIGHTI aperture actuators and the ICP. The MIGHTI is shown graphically in Figure 8.

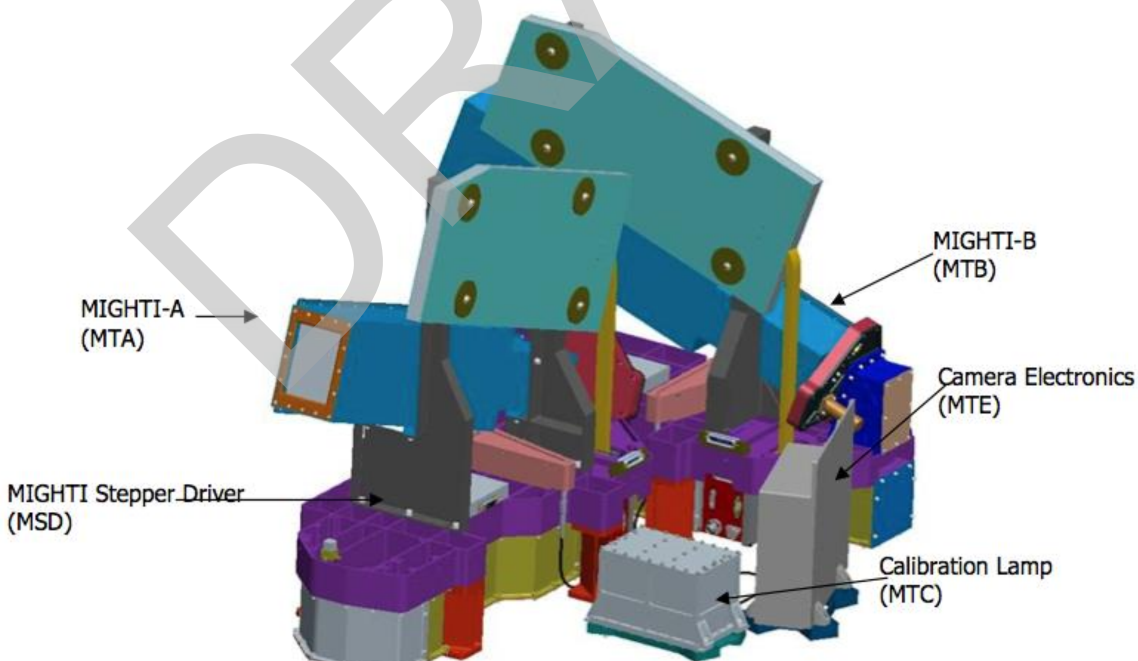


Figure 8 ICON MIGHTI Instrument

The MIGHTI instrument is one of two for ICON that has moving parts used regularly during flight. An aperture at the rear of the baffle, and another aperture operated simultaneously as an internal Lyot stop, provide a reduction to 15% of the full aperture, in a manner that prevents light scattered by the daytime atmosphere from reaching the first mirror. Specific details of this capability are discussed in the companion paper that describes the instrument in detail [Englert et al., this issue]

4.2 ICON Ion Velocity Meter (IVM)

The IVM is supplied by the University of Texas at Dallas (UTD). It will be used to determine the electric field perpendicular to the magnetic field and the ion motion parallel to the magnetic field through measurement of the ion drift velocity vector. Two full IVM instruments, IVM-A and IVM-B, are carried by ICON. Two sensors are part of each of these IVM instruments, the Retarding Potential Analyzer (RPA) and a Drift Meter (DM), which together provide data to determine the total ion concentration, the major ion composition, the ion temperature and the ion velocity in the spacecraft reference frame. An individual IVM instrument is shown graphically in Figure 9. As shown in Section 5, these are mounted on opposite faces of the instrument, providing the capability to meet threshold science if IVM and MIGHTI together in either northern or southern-facing modes. Unlike the MIGHTI instrument, only one IVM will be powered and operated at any time in nominal science mode, IVM-A when ICON and MIGHTI are northern-facing and IVM-B when south.

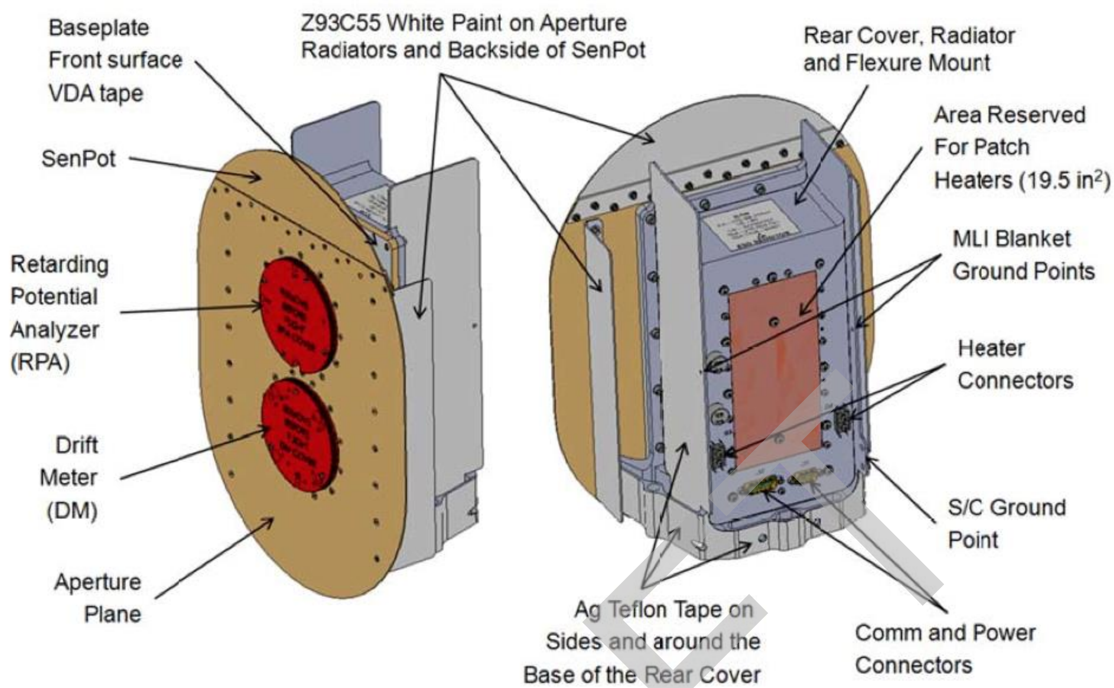


Figure 9 ICON Ion Velocity Meter (IVM)

There are in fact two IVM instruments on ICON, facing in opposite directions. The full build and performance discussion of the instrument is reported in a companion to this paper [Heelis *et al.*, this issue]

4.3 ICON Far-Ultraviolet Imager (FUV)

The ICON FUV instrument is a spectrographic imager. The FUV determines the daytime thermospheric composition by measuring the intensity profile of the O and N_2 emissions and infers the ion density. The FUV measures nighttime plasma density by imaging 135.6-nm emission of O atoms produced in recombination of O^+ ions with electrons. The FUV instrument is shown in Figure 10. The turret contains a steerable mirror which allows the steering of the field of view ±30° in the horizontal plane. Routinely the instrument will make limb altitude profile of the 135.6-nm emission and of the LBH emissions of N_2 near 157 nm during the day. The instrument is provided with a digital image processing capability located in the Instrument Control Package to reduce the blur due to motion of the spacecraft during imaging integrations. This motion compensation, termed Time-Delay Integration (TDI) accounts for the range to limb tangent points and disk views below the limb, and supports 13 separate turret angles within this range.

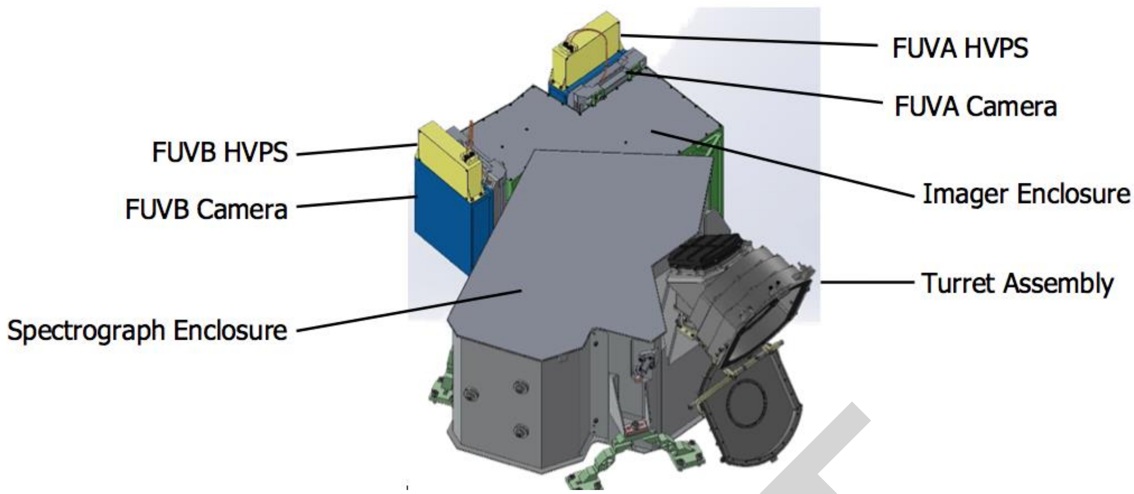


Figure 10 ICON Far-Ultraviolet Imager (FUV)

The FUV turret and TDI imaging mode are only operated at night, providing capability to image structure in the ionospheric plasma at the limb (at tangents 1200-2000 km from the spacecraft). This capability allows FUV to identify regions of disturbed plasma densities that should be excluded from analyses of large-scale tidal forcing (Objective 2). The FUV instrument is described in a companion paper [Mende et al., this issue] and the function of the TDI feature is described at length in the companion paper on the. [Wilkins et al., this issue]

4.4 ICON Extreme-Ultraviolet Spectrometer (EUV)

The ICON EUV is an imaging spectromter. It measures the altitude intensity profile and spatial distribution of ionized oxygen (O^+ 83.4nm and 61.7nm) emissions on the limb in the thermosphere while rejecting the He 58.4nm line, as well as all bright FUV emissions longward of ~900 nm wavelength. Major elements of EUV are illustrated in Figure 11.

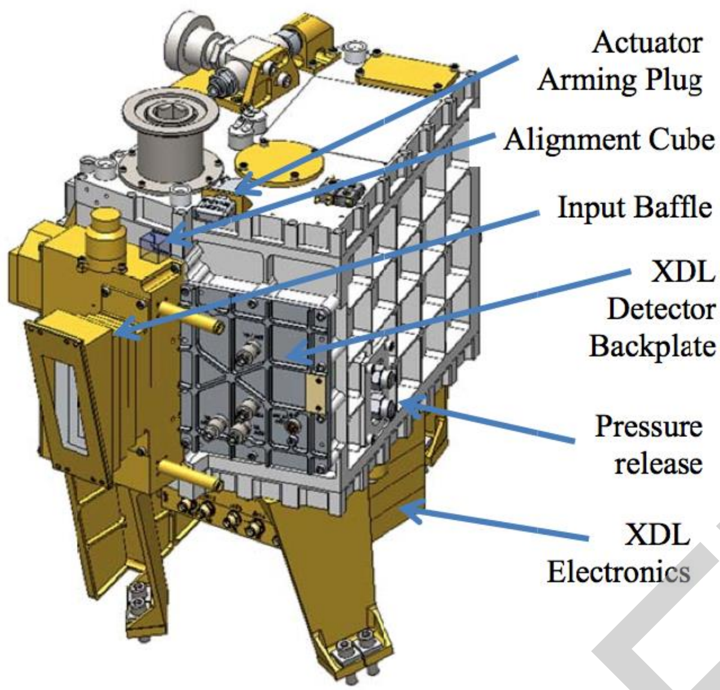


Figure 11 The ICON EUV Instrument

The complete description of the EUV instrument is provided in the companion paper to this report [Edelstein et al., this issue].

4.5 Instrument Operations

The ICON imaging instruments change states depending on whether the instrument FOVs are in daylight or night. MIGHTI changes integration time between 30 (day) and 60 (night) seconds. In daylight, FUV lowers the intensifier gain and takes TDI images of 2 channels co-added into vertical profiles every 12 seconds. At night, FUV takes full TDI images of the 135.6nm channel only (4x16km pixels) every 12 seconds and the FUV scan mirror views along local magnetic meridian. EUV is turned off at night. The spacecraft magnetic torque bars, used as part of the attitude determination and control system, are only used 15 degrees of magnetic latitude away from the dip equator, and then only during 12 s in successive 32 s periods. This provides IVM samples from the magnetic equatorial region uncontaminated by torqueing fields, and usable IVM data away from the equator. A summary of these different states is provided in Table 2.

Sensor	*Day Configuration*	*Night Configuration*
MIGHTI A/B	30 s integration 15% aperture	60 s integration 100% aperture
FUV Channel 1 (135.6)	12 s integration	12 s integration, turret motion in 10° steps between some integrations
FUV Channel 2 (LBH)	12 s integration	High Voltage Off
EUV	12 s integration	High Voltage Off
IVM A/B	4 s samples	4 s samples
Mag Torque Bars	12 s on / 20 s off outside of ± 15° CGM latitude only	12 s on / 20 s off outside of ± 15° CGM latitude only

Table 2 - Instrument operating modes in Day and Night Mode. MIGHTI A/B will be synchronized to terminator crossings of the FOV, and so will have differently timed occurrences of Day/Night modes (5-6 minute differences at each terminator crossing).

4.6 Science Data Products

The four instruments of the science payload produces all of the data products of the ICON mission. Those products are listed below. Each of these products from Level 1 to 4 will be available in NetCDF formats.

Level 0 are unprocessed outputs from the ICP. For MIGHTI, EUV and IVM, these are essentially direct outputs from the sensors, either CCD readouts (MIGHTI), electric currents (IVM), or integrated counts from the crossed delay line detector (EUV). FUV goes through additional processing steps, and direct CCD readouts are only provided in engineering modes.

Level 1 data from the remote sensing data are reported in calibrated radiances (EUV and FUV), and in the particular characteristics of the MIGHTI infrared filters and interferogram parameters such as phase shifts. For IVM, the arrival angles at the driftmeter are reported, as well as the current vs. voltage relationships determined in every RPA voltage sweep.

Level 2 products are retrieved geophysical parameters. For IVM, these require a calculation and conversion to plasma drift parameters in the frame of references of the rotating Earth (Heelis et al., this issue). For the remote sensing instrument, these products all require the application of a retrieval algorithm to determine the geophysical parameters from the limb radiances. These retrievals vary in sophistication needed to meet the science requirements, and are discussed in companion papers to this one in this issue. (Stevens et al., Harding et al., Kamalabadi et al., Stephan et al., this issue). Level 3 products are daily summaries of the L2 products, and will likely be used to rapidly create browse products.

Level 4 products are outputs of the first principles and assimilative models that are regularly run to support the ICON science investigation. Outputs of all instruments are incorporated into the L4 products, by several pathways. The HME (ref) product incorporates temperature and winds from MIGHTI, which then informs the TIEGCM (ref) and subsequent SAMI3 (ref) model runs. Both daytime and nighttime ionospheric measurements are incorporated into the IDA4D (ref) assimilation, using the EUV L2 ionospheric profiles and the FUV L1 calibrated LOS radiances directly.

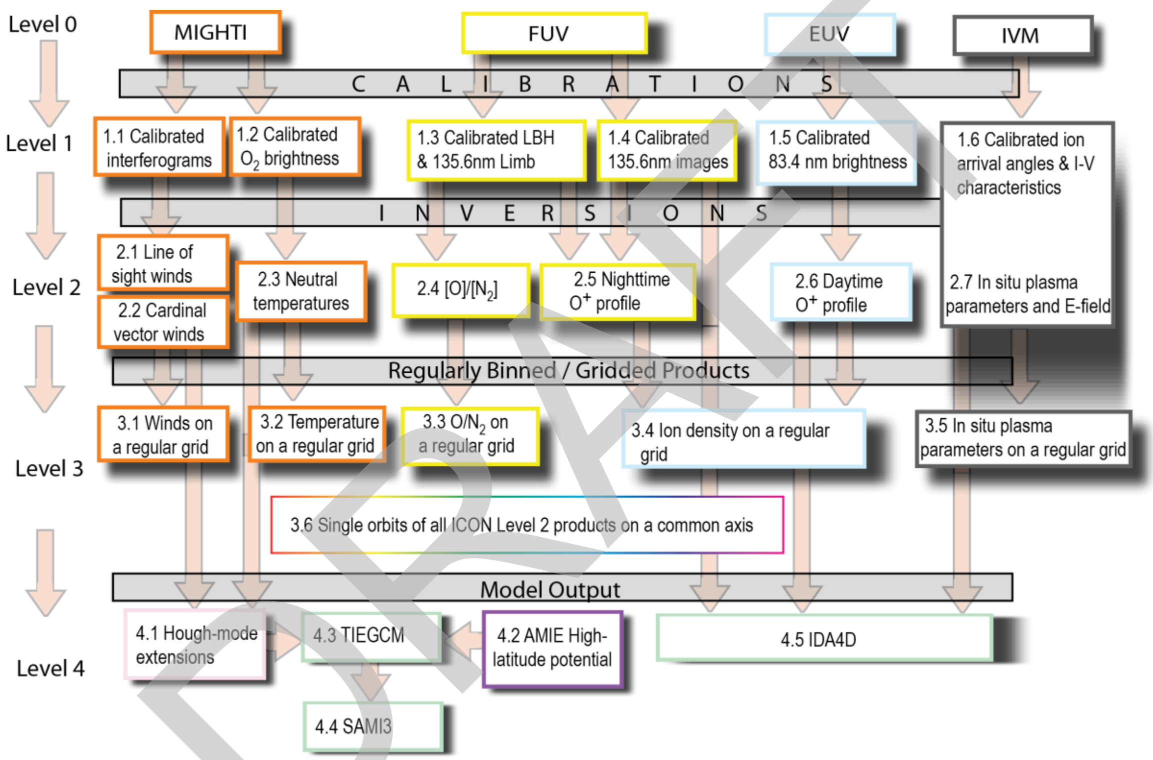


Figure 12 - The science data products for the ICON mission.

5. Science Payload Design

5.1 Payload Control, Data, and Power

The power and data interface for all ICON science instruments resides in the Instrument Control Package, or ICP, which is provided by the University of California, Berkeley (UCB). It provides the electronic interface between the Spacecraft bus and the Instrument sensors.

The ICP consists of four boards illustrated in Figure 13. These boards provide the science payload all of its power, instrument control and data processing capability. The primary data interface for all instruments is provided by the Data Control Board (DCB). Data from these instruments is transferred to solid state memory on the DCB where an embedded processor will provide CCSDS-compliant packetization and eventual transfer to a solid state recorder in the spacecraft bus. The Power Control Board (PCB) controls power to the MIGHTI and monitors current, while the LVPS provides power to the EUV and FUV instruments. The TEC Power Supply (TPS) provides computer-controlled power to the thermoelectric coolers in the MIGHTI cameras, used to cool the CCDs.

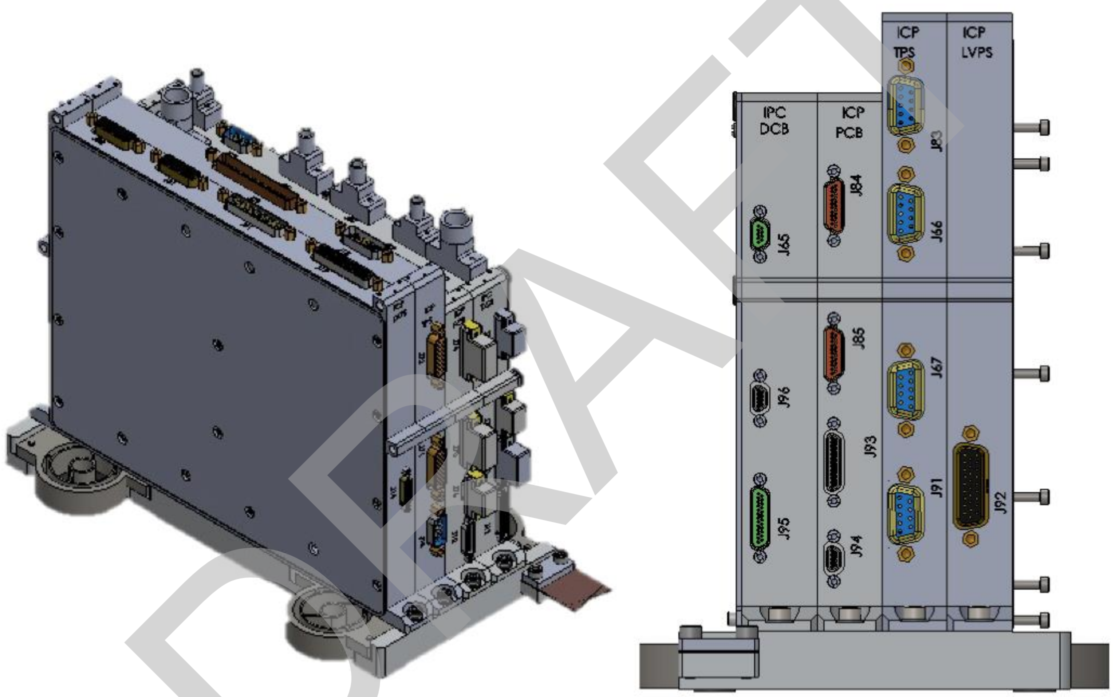
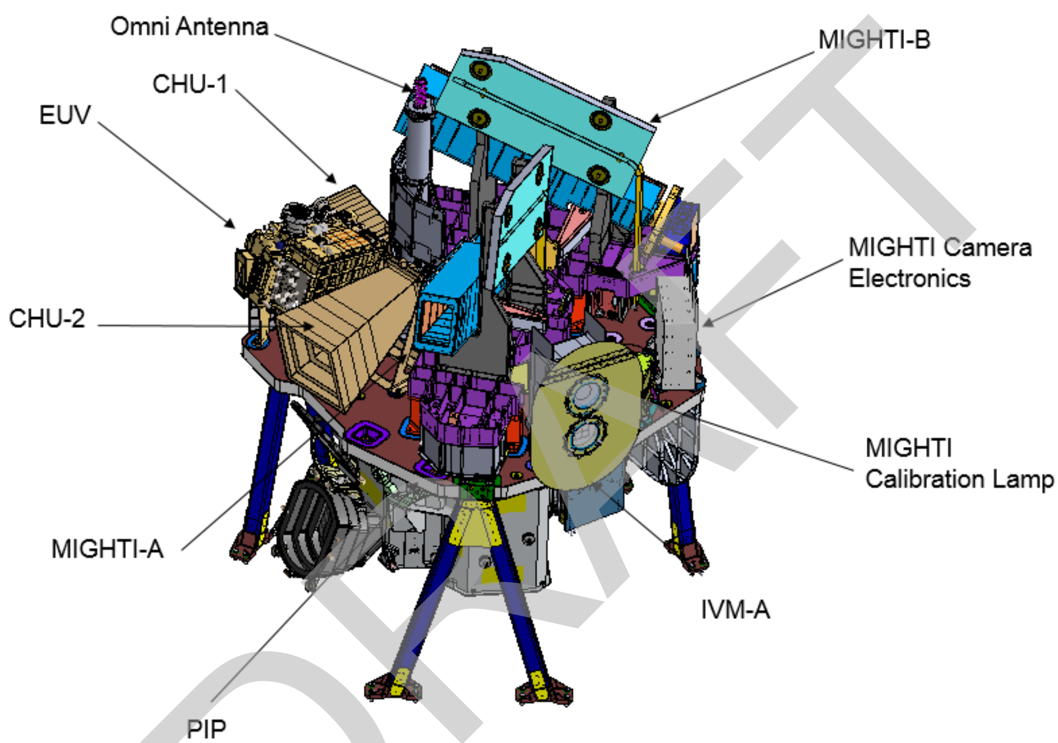


Figure 13 – The ICON ICP

The ICP also serves to process 2D FUV images using a Time-Delay Integration (TDI) algorithm that provides motion compensation during the accumulation of individual CCD readout frames at 10 Hz (120 frames co-added in each integration).

5.2. Payload Mechanical and Thermal

The ICON science payload carries all of the science instruments and supporting harnessing and attachment points. The payload is integrated on a Payload Interface Plate (PIP) that connects physically to the spacecraft by three carbon-fiber-based bipods. Each side of the PIP is populated with instruments and their supporting components, as well as spacecraft components consisting of 2 star trackers, the navigational magnetometer, and the S-Band antenna. The MIGHTI boresights are directed to provide two roughly orthogonal lines-of-sight at a continuous tangent height approximately 1500 km from the orbital plane, which in the baseline configuration with IVM-A directed in the ram direction is to the port side, or north of the orbit track.



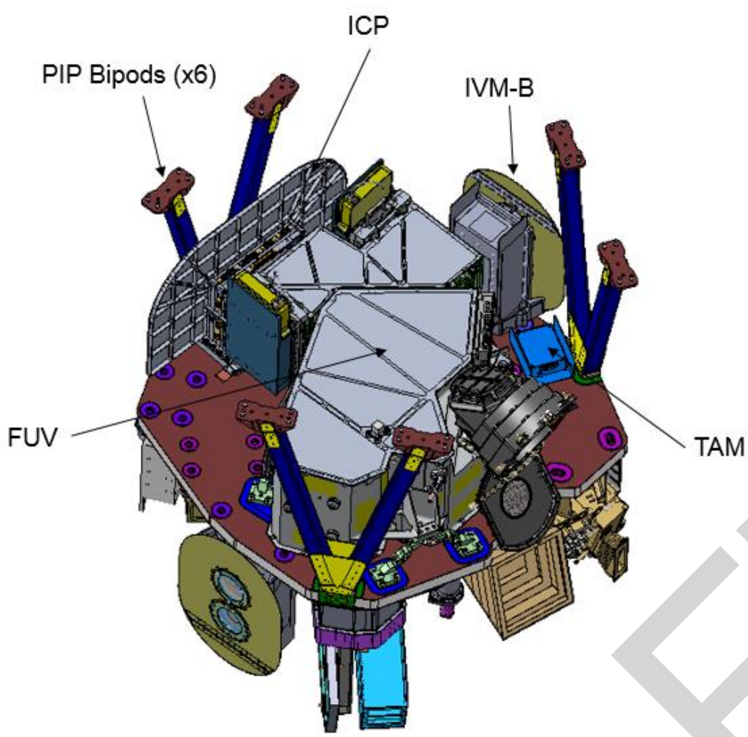
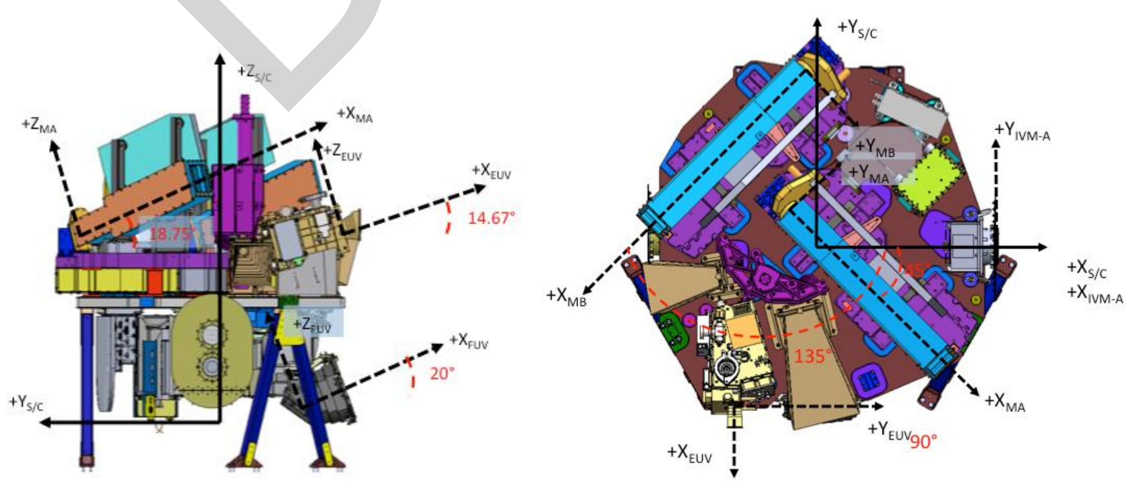


Figure 13 – A model of the ICON science payload, viewed from a point above its Earth-facing side (Figure 13a), and also from the side that will face the spacecraft (Figure 13b).

5.3 Payload Views and Pointing



Instrument	Full Angle FOV (deg)	
	Vertical	Horizontal
EUV	***16***	***12***
FUV	***24***	***18***
MIGHTI A	***5.74***	***3.22***
MIGHTI B	***5.74***	***3.22***
IVM-A	***45***	***45***
IVM-B	***45***	***45***

Figure 14 – The angular boresights and extent of fields of views of each of the instruments as designed. Final values are determined prior to launch and validated during in-flight 30-day checkout. IVM values are keepout zones. Abbreviations MA,B are MIGHTI-A and MIGHTI-B, S/C is Spacecraft, which defines the observatory coordinate system.

From the vantage point of its planned 575 km circular orbit, the ICON remote sensing instruments are pointed toward Earth's limb. Expected altitude ranges are reported in the companion papers for each instrument. The primary flight rule during science operations is to direct the bottom of the fields of view of both MIGHTI A and B to a tangent altitude of 90 km. This is performed regularly to account for terrestrial obliquity, and will be implemented for observatory orbits that deviate from nominal, which will occur naturally during the science mission. In terms of departures from exact nadir pointing of the payload, this requires rotations of the observatory in both pitch and roll. The pitch of the observatory (rotation about its $\boldsymbol{Y}$ axis) accounts mainly for the differences in tangent altitudes at constant angles from spacecraft nadir due to Earth's oblique shape, and a roll of the observatory (rotation about its $\boldsymbol{X}$ axis) accounts for altitude changes of the observatory. ICON is designed to meet its science requirements across the full range of altitudes from 450 km to 610 km, altitude range representing a 3-sigma orbit insertion error of the Pegasus launch vehicle.

6. Observatory and Mission Design

6.1 Observatory Design

The ICON spacecraft is based on Orbital's LEOStar-2/750 platform, following the design established on missions such as GALEX, AIM, OCO, and NuSTAR but incorporating a new single avionics box called the Master Avionics Unit (MAU) that performs all Command and Data Handling (C&DH) tasks while also providing control of the Electric Power Subsystem (EPS). Its design conforms to several driving science requirements of the mission.

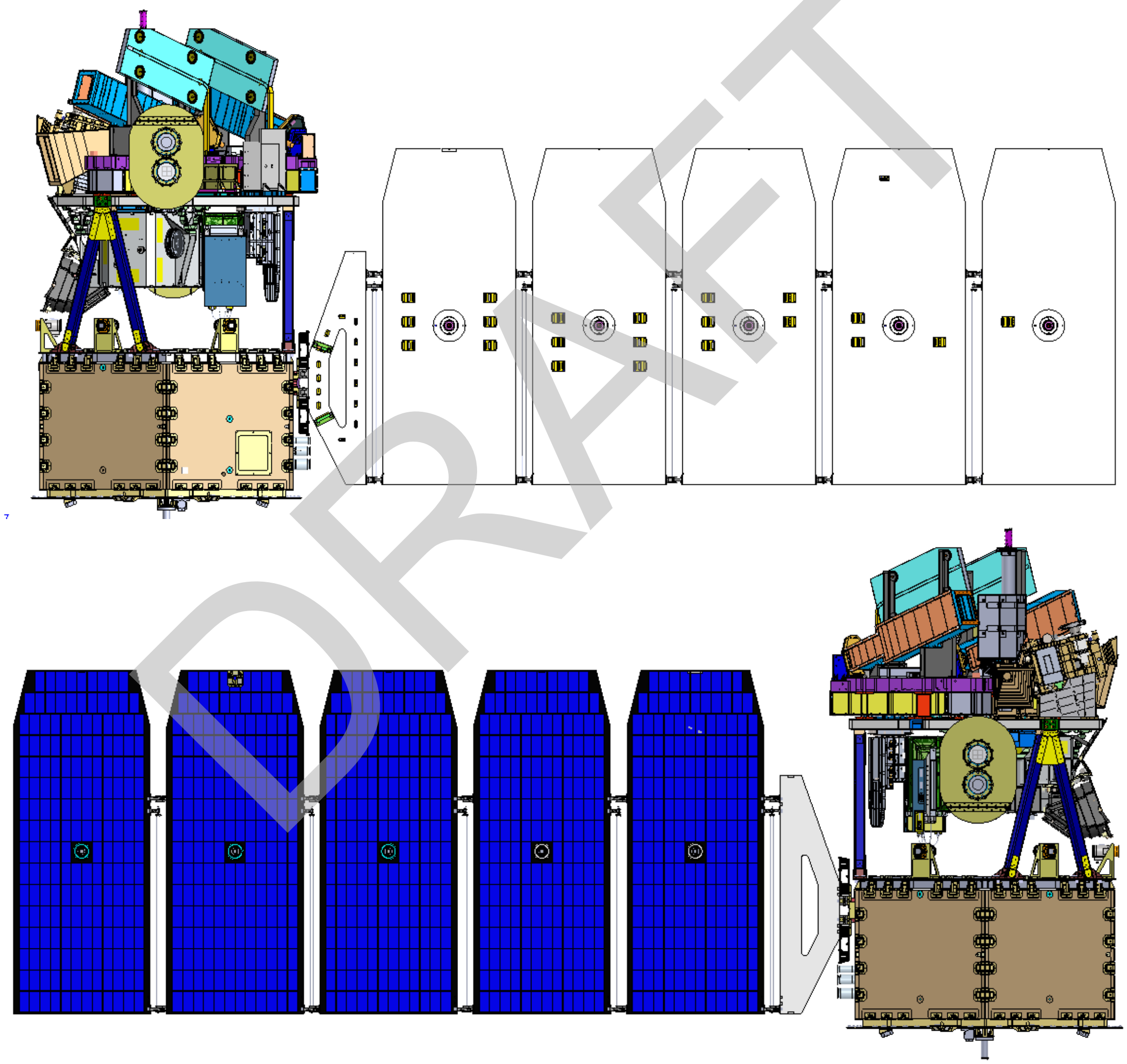


Figure 15 – The ICON observatory with solar array deployed

6.2 Science Mission Design

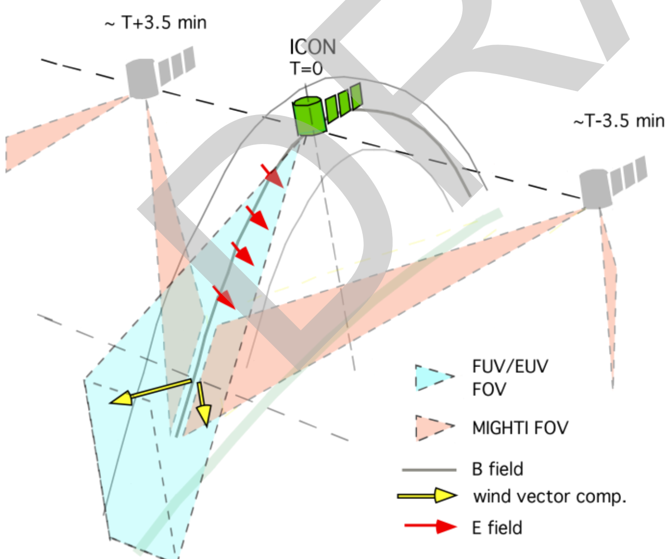


Figure 16 – Geometry of the ICON observations required for Science Objective 1. ICON is shown near the magnetic equator. At position (2) T=0 FUV and EUV instruments view the limb thermosphere/ionosphere (Fields Of Views shown in light blue) while the IVM measures the in situ ion drift, representative of the E×B field (red arrows). The interferometers measure the relevant

wind vector components (purple) at positions (1) T-3.5 min and (3) T+3.5 min. The distance to the tangent points where the interferometers make the measurements varies with altitude the same way as the distance of dipole field line from the satellite.

ICON's design allows it to make observations necessary to address its 3 science objectives, measuring the key parameters that influence the coupling of the ionosphere and thermosphere. In any 7-minute period it makes all of these measurements, including the neutral wind profiles that are so crucial for understanding the daytime variability of the ionosphere.

ICON will only spend some fraction of any orbit in the geometry shown in Figure 16, where the observatory is in the immediate vicinity of the apex of a magnetic field line. On average during a day, this fraction is a basic function of orbital inclination. A study of the effect of orbital inclination is summarized in Table 17. For latitudes equatorward of ~15°, ICON would not cross the magnetic equator at every longitude, thus no inclination below 15° is acceptable for complete equatorial coverage. At latitudes higher than ~30°, the time ICON spends in this region drops below 100 minutes per day, which would still permit the investigation required for Science Objective 1, but is less than ideal. The length of time per orbit that ICON remains in the required viewing geometry is also an important consideration. Because only daytime data between 9-15 hours LT are used for Science Objective 1, each daytime pass must be considered in isolation and thus the longer ICON spends per orbit in the required viewing geometry, the better that gradients and spatial scales of variability can be determined. *Table* shows that the maximum duration decreases by a factor of 2 going from 15 to 27° orbital inclination, but reduces by a further factor of 2 going from 30 to 45°. Thus, the optimum orbital inclination to address Science Objective 1 alone is between 15-30°. Notably, inclinations of 54° and larger cannot ever provide the geometry to make comparable observations. Note that Science Objectives 2 and 3 also influence the decision of the orbital inclination selected for ICON, each of which benefit from inclinations that provide middle latitude observations. For these and other reasons, the inclination of ICON is selected in the high end of the range.

Orbital inclination	Time per day in optimal viewing geometry	Maximum duration with optimal viewing within a single orbit
0°	330 min	45 min (0 min in S. American sector)

15°	213 min	45
27°	108 min	25
45°	67 min	10

Table 17 The effect of changing ICON's orbital inclination on the length of time per day and per orbit that ICON is in the orbital viewing geometry for Objective 1.

Conjugate Operations

ICON's Conjugate Operation is required to gather the observations for the direct comparison of the magnetically connected winds and ion drifts. The Conjugate Operation involves a sequence of 4 yaw maneuvers shown in *Figure 18*. Through this sequence of maneuvers, ICON is able to observe the horizontal neutral winds along both the northern and southern dynamo regions connected to the *in situ* drifts, allowing for a complete determination of the dynamo drivers, all while maintaining the critical observing geometry shown in Figure 16. It also makes a series of EUV measurements during the sequence, further informing the determination of ionospheric conductance. This sequence will be performed as ICON is crossing the geomagnetic equator during daylight, usually between 9 and 15 LT. The Conjugate Operations maneuver will occur no more than 1-2 times per day. These will provide critical information in addition to the survey ICON data for Objective 1, which is collected on the 13-14 orbits per day that do not include a conjugate operation.

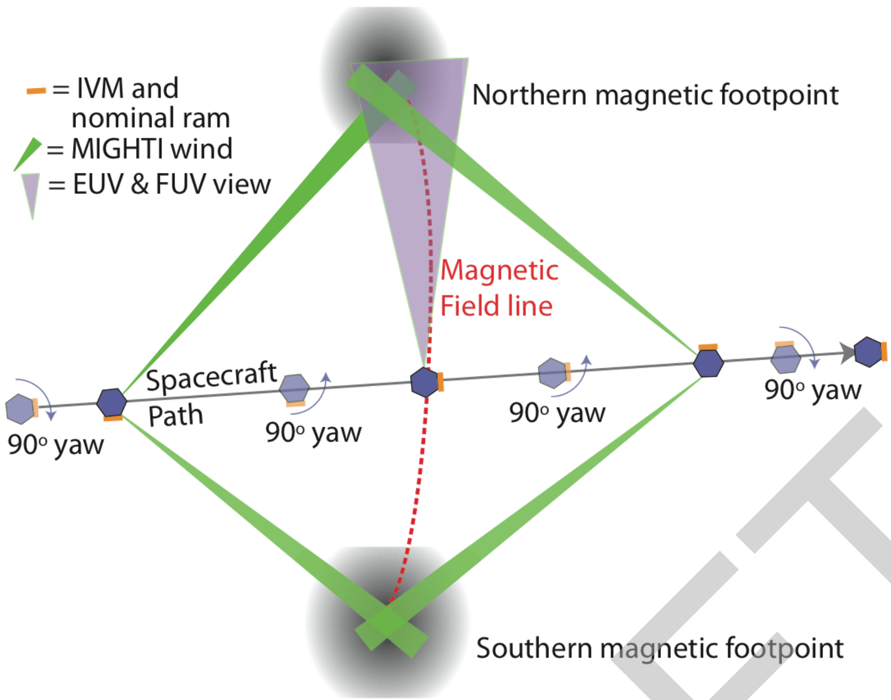


Figure 18 Cartoon of the conjugate observations. At pre-scheduled times when the geometry is correct, ICON initiates four timed yaw maneuvers (approximately -90°, +90°, +90° and -90°, exact angle depends on declination and initial orientation of the observatory) to make wind observations at two magnetically conjugate points.

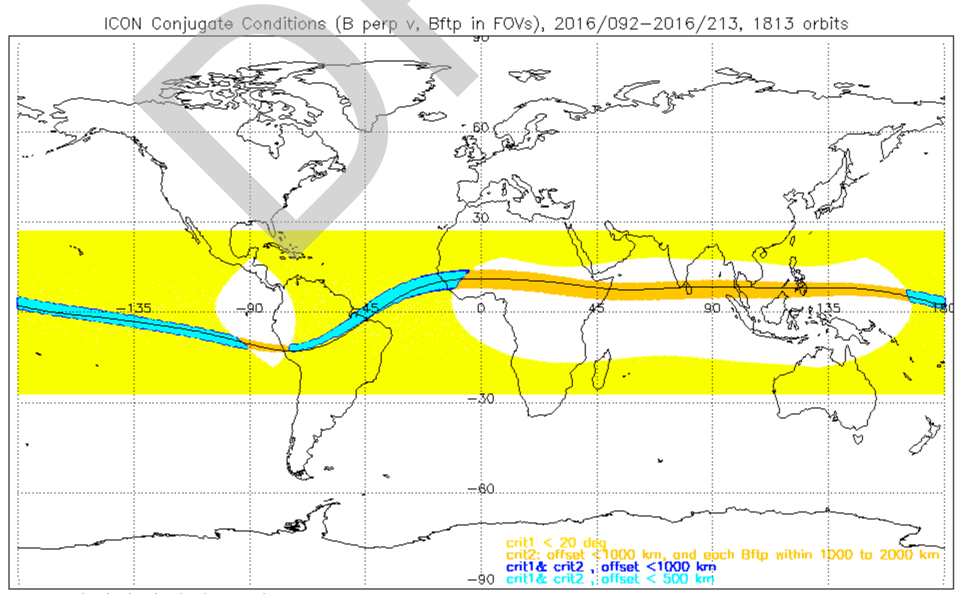


Figure 19 showing regions in blue where Conjugate operations may be centered in order to match northern and southern footpoint observations that are also magnetically conjugate. The combined offset of the wind measurements from the conjugate points is never 0 km but often less than 500 km, the width of two MIGHTI wind samples on the limb.

6.3 Mission Operations Design

6.1 Concept of Operations

6.2 Launch, Early Ops and Checkout

The operations timeline for the first month of the mission is shown in Table 20

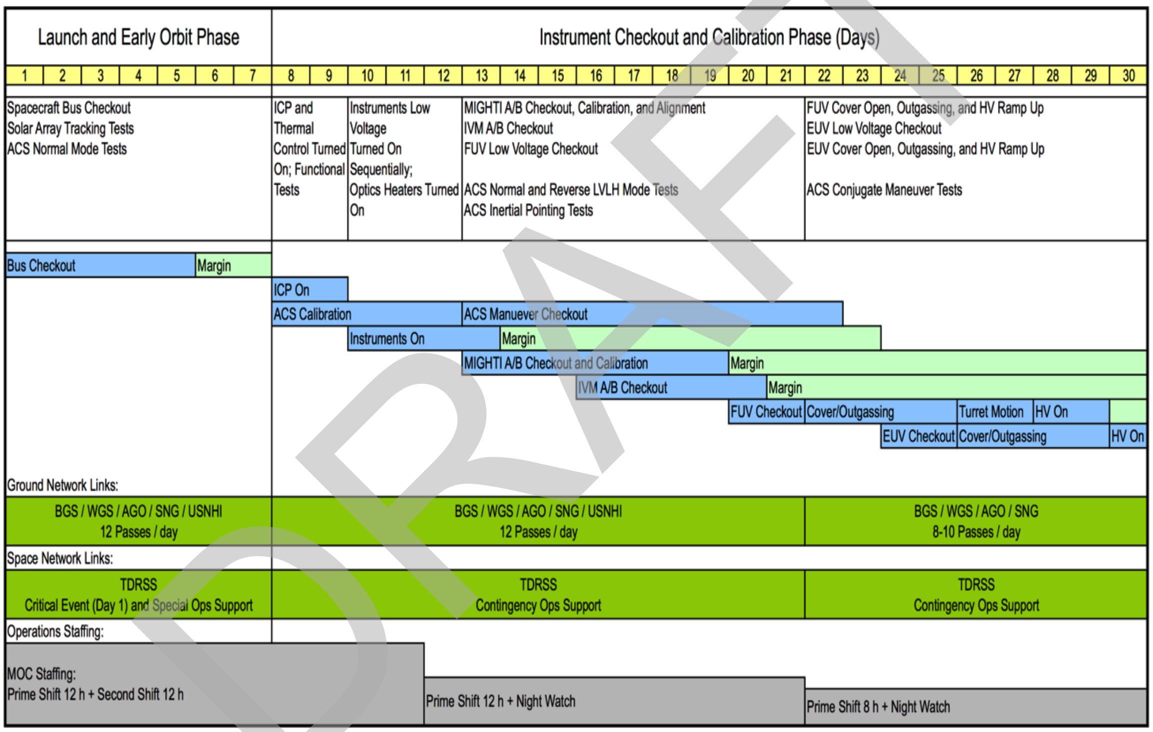


Table 20

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