Appendix A
Why Is the Ionosphere Important?

The ionosphere is the part of the earth's atmosphere beginning at an altitude of about 30 miles and extending outward 1,200 miles or more. This region consists of layers of free electrically charged particles that transmit, refract, and reflect radio waves, allowing those waves to be transmitted great distances around the earth. The interaction of the ionosphere on impinging electromagnetic radiation depends on the properties of the ionospheric layer, the geometry of transmission, and the frequency of the radiation. For any given signal path through the atmosphere, a range of workable frequency bands exists. This range, between the maximum usable frequency (MUF) and the lowest usable frequency (LUF), is where radio waves are reflected and refracted by the ionosphere much as a partial mirror may reflect or refract visible light.[56] The reflective and refractive properties of the ionosphere provide a means to transmit radio signals beyond direct "line-of-sight" transmission between a transmitter and receiver. Ionospheric reflection and refraction has therefore been used almost exclusively for long-range HF (from 3 to 30 MHz) communications. Radio waves with frequencies ranging from above 30 MHz to 300 GHz are usually used for communications requiring line-of-sight transmissions, such as satellite communications. At these higher frequencies, radio waves propagate through the ionosphere with only a small fraction of the wave scattering back in a pattern analogous to a sky wave. Communicators receive significant benefit from using these frequencies since they provide considerably greater bandwidths and thus have greater data-carrying capacity; they are also less prone to natural interference (noise).

Although the ionosphere acts as a natural "mirror" for HF radio waves, it is in a constant state of flux, and thus, its "mirror property" can be limited at times. Like terrestrial weather, ionospheric properties change from year to year, from day to day, and even from hour to hour. This ionospheric variability, called space weather, can cause unreliability in ground- and space-based communications that depend on ionospheric reflection or transmission. Space weather variability affects how the ionosphere attenuates, absorbs, reflects, refracts, and changes the propagation, phase, and amplitude characteristics of radio waves. These weather dependent changes may arise from certain space weather conditions such as: (1) variability of solar radiation entering the upper atmosphere; (2) the solar plasma entering the earth's magnetic field; (3) the gravitational atmospheric tides produced by the sun and moon; and (4) the vertical swelling of the atmosphere due to daytime heating of the sun.[57] Space weather is also significantly affected by solar flare activity, the tilt of the earth's geomagnetic field, and abrupt ionospheric changes resulting from events such as geomagnetic storms.

In summary, the ionosphere's inherent reflectivity is a natural gift that humans have used to create long-range communications connecting distant points on the globe. However, natural variability in the ionosphere reduces the reliability of our communication systems that depend on ionospheric reflection and refraction (primarily HF). For the most part, higher frequency communications such as UHF, SHF, and EHF bands are transmitted through the ionosphere without distortion. However, these bands are also subject to degradation caused by ionospheric scintillation, a phenomenon induced by abrupt variations in electron density along the signal path, resulting in signal fade caused by rapid signal path variations and defocusing of the signal's amplitude and/or phase.

Understanding and predicting ionospheric variability and its influence on the transmission and reflection of electromagnetic radiation has been a much studied field of scientific inquiry. Improving our ability to observe, model, and forecast space weather will substantially improve our communication systems, both ground and space-based. Considerable work is being conducted, both within the DOD and the commercial sector, on improving observation, modeling, and forecasting of space weather. While considerable technical challenges remain, we assume for the purposes of this study that dramatic improvements will occur in these areas over the next several decades.

Appendix B
Research to Better Understand and Predict Ionospheric Effects

According to a SPACECAST 2020 study titled, "Space Weather Support for Communications," the major factors limiting our ability to observe and accurately forecast space weather are (1) current ionospheric sensing capability; (2) density and frequency of ionospheric observations; (3) sophistication and accuracy of ionospheric models; and (4) current scientific understanding of the physics of ionosphere-thermosphere-magnetosphere coupling mechanisms.[58] The report recommends that improvements be realized in our ability to measure the ionosphere vertically and spatially; to this end an architecture for ionospheric mapping was proposed. Such a system would consist of ionospheric sounders and other sensing devices installed on DoD and commercial satellite constellations (taking advantage in particular of the proposed IRIDIUM system and replenishment of the GPS) and an expanded ground-based network of ionospheric vertical sounders in the US and other nations. Understanding and predicting ionospheric scintillation would also require launching of an equatorial remote sensing satellite in addition to the currently planned or deployed DOD and commercial constellations.

The payoff of such a system is an improvement in ionospheric forecasting accuracy from the current range of 40-60 percent to an anticipated 80-100 percent accuracy. Daily worldwide ionospheric mapping would provide the data required to accurately forecast diurnal, worldwide terrestrial propagation characteristics of electromagnetic energy from 3-300 MHz. This improved forecasting would assist satellite operators and users, resulting in enhanced operational efficiency of space systems. It would also provide an order of magnitude improvement in locating the sources of tactical radio communications, allowing for location and tracking of enemy and friendly platforms.[59] Improved capability to forecast ionospheric scintillation would provide a means to improve communications reliability by the use of alternate ray paths or relay to undisturbed regions. It would also enable operational users to ascertain whether outages were due to naturally occurring ionospheric variability as opposed to enemy action or hardware problems.

These advances in ionospheric observation, modeling, and prediction would enhance the reliability and robustness of our military communications network. In addition to their significant benefits for our existing communications network, such advances are also requisite to further exploitation of the ionosphere via active modification.

Appendix C
Acronyms and Definitions

AOC	air operations center
AOR	area of responsibility
ATO	air tasking order
EHF	extra high frequency
GWN	global weather network
HF IR	high frequency infared
LF	low frequency
LUF	lowest usable frequency

Mesoscale	less than 200 km2
Microscale	immediate local area
MUF	maximum usable frequency
MW OTH PGM	microwave over-the-horizon precision-guided munitions
RF	radio frequency
SAR SARSAT	synthetic aperture radar search and rescue satellite-aided tracking
SHF SPOT	super high frequency satellite positioning and tracking
UAV UV	uninhabited aerospace vehicle ultraviolet
VHF	very high frequency
WFS	weather force specialist
WFSE	weather force support element
WX	weather

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