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Space Environment Engineering and Science Applications Workshop – Ionospheric Impacts: Precision Applications (Precision Agriculture)

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Executive Summary

Space weather (SpWx) impacts civilian technology that is used in our everyday life, ranging from personal technology, like cell phones, to national infrastructures, such as the power grid. Some of the most difficult challenges to the study of SpWx are understanding and communicating the interconnection of the space environment to technology and end users. The Aerospace Corporation supported an initiative to tackle these challenges, with the goals to (1) identify specific current and future difficulties facing specific user groups due to ionospheric disruptions, and (2) develop potential strategies for addressing them through a combination of mitigation strategies, including the SpWx research, technology, operations, and end-user communities. Precision navigation technologies utilizing Global Navigation Satellite Systems (GNSS), such as the Global Positioning System (GPS), were selected as the first focus area, with an emphasis on the precision agriculture (PA) user community.

The following report summarizes the information presented and subsequent findings from a two-day workshop, the Space Environment Engineering and Science Applications Workshop – Ionospheric Impacts: Precision Agriculture (SEESAW-II), that brought together members of the PA end-user community, technology engineers and researchers, and SpWx researchers and forecasters. The early sections of the report provide a contextual overview of PA and SpWx meant to be accessible to nonexperts and provide a common level of knowledge for subsequent discussions. The final section of the report documents the five most important observations during the workshop:

1. The determination of signal disruption sources is key for real-time operations and future technology/system developments.

2. Multi-frequency GNSS systems will likely mitigate the day-to-day quiet and moderately disturbed ionospheric variability impacts on PA end users.

3. Ionospheric nowcasts of ionospheric conditions indicative of signal degradation or loss of lock would enable performance improvements to PA navigation system.

4. The most significant economic impacts due to ionospheric conditions occur at low latitudes where intense, more frequent ionospheric scintillation occurs.

5. The communities represented at the workshop were generally unaware of the available resources, data, and technology available to assist in their respective area of operation and research.

Each observation is followed by a discussion of potential strategies to address them now and in the future. This report is intended to be an initial bridge between the communities that will continue to grow through further discussions and collaborations.

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1. Introduction

1.1 Purpose and Objectives

Space weather (SpWx) has everyday impacts on civilian technology outside of the space enterprise. Some of the most often stated impacted applications are commercial aviation and power grid disruptions. However, many other application areas may be impacted by SpWx, but may be unaware of the potential severity. One of the largest challenges faced by the SpWx operational and forecast communities, in addition to providing more accurate forecasts and nowcasts, is the ability to connect to end users, understand their needs, and tailor products and communication to specific applications. From the technology user perspective, many may not be aware of the contribution of SpWx to their systems' anomalies and/or issues or, if they are aware, may attribute it to the incorrect SpWx phenomenology. To assist in bridging the communication gap between SpWx researchers and end users, The Aerospace Corporation organized and hosted a workshop focused on a specific application: precision agriculture (PA).

Table 1. SEESAW-II Planning Committee

Name	Position	Organization
Dr. Rebecca Bishop	Principal Scientist	The Aerospace Corporation
Dr. Ken Sudduth	Supervisory Agricultural Engineer	USDA – Agricultural Research Service
Dr. Alisa Coffin	Ecologist	USDA – Agricultural Research Service
Mr. Stuart Riley	Vice President	Trimble
Mr. William Murtagh	Program Coordinator	NOAA Space Weather Prediction Center
Dr. Steve Lewis	Senior Engineering Specialist	The Aerospace Corporation
Dr. Howard Singer	Chief Scientist	NOAA Space Weather Prediction Center
Dr. Joseph Mazur	Principal Director, Space Science Applications Lab	The Aerospace Corporation
Mr. Mark Rentz	Principal Design Engineer	John Deere
Ms. Pat Doherty	Director, Institute for Scientific Research	Boston College
Mr. Bob Rutledge	Director, Space Science Department	The Aerospace Corporation
Dr. Elsayed Talaat	Director, Office of Projects, Planning, and Analysis	NOAA National Environmental Satellite, Data, and Information Service
Mr. Bart Ciastkowski	Manager, Applications Engineering & Technical Support	Septentrio
Mr. JJ Cabrera-Guzman	Research Associate	The Aerospace Corporation

1.2 Workshop Organization

The Space Environment Engineering and Science Applications Workshop – Ionospheric Impacts: Precision Agriculture was held virtually over two days in June and July 2021. The workshop's goal was to bring together a focused group from the research, engineering, operational, and user communities to discuss in detail issues experienced by the PA community, determine the extent the ionosphere causes or influences those issues, and how the SpWx research/forecast community could better serve the needs of the PA users. The first step in organizing the workshop was to identify key people in the different communities to participate on the core planning committee. The resulting committee (see Table 1) consisted of representatives from PA technology companies, space weather researchers/forecasters, and

PA researchers. The planning committee provided an initial list of suggested people to invite and the list was expanded as people who were invited made further suggestions. The final list consisted of approximately 90 invitees. The final number of registered participants was 55, with 45 and 40 participants at the Day 1 and Day 2 workshops, respectively.

Table 2. SEESAW-II Day 1 Agenda

Title	Presenter	Organization
Introduction	Dr. Rebecca Bishop	The Aerospace Corporation
Storms from the Sun: The Science of Space Weather	Ms. Patricia Doherty	Boston College
Trimble Ionospheric Overview	Dr. Stuart Riley	Trimble
Precision Agriculture and the Road to Autonomy	Mr. Steve Rounds	John Deere
GNSS Receiver Technology: Leveraging Ionospheric Observations for Improved Precision Agriculture Support	Mr. Bart Ciastkowski	Septentrio
Global Cost Assessment of GNSS Outage to Agricultural Productivity	Dr. Terry Griffin	Kansas State University
What do you want from me? A Forecaster's perspective on space weather support.	Mr. Rob Steenburgh	NOAA, SWPC
Precision Agriculture and Civil GPS Disruption Reporting	Dr. Steve Lewis	The Aerospace Corporation
Topics Introduction	Dr. Rebecca Bishop	The Aerospace Corporation

Day 1 (Table 2) consisted of a series of overview presentations geared to present a well-rounded understanding of the technology and economic impact related to GNSS degradation and loss and an overview of the SpWx conditions leading to ionospheric disturbances capable of disruption. Day 2 consisted of open technical discussions among all attendees to probe deeper into two topics: (1) "How do existing systems and projects minimize ionospheric impacts?" and (2) "What type of future technology and ionospheric monitoring/forecasting is needed?" Table 3 lists the two focus topics along with possible areas to be considered during the discussions. At the end of Day 2, major themes, future recommendations, and potential follow-on activities were identified.

Table 3. SEESAW-II Day 2 Topics

Topic	Areas to Consider
How do ***existing*** systems and projects minimize ionospheric impacts?	• Special Operations and/or Planning • Other Anomaly Reporting/Identification • Space Weather Forecast Uses • Other Types of Systems
What type of ***future*** technology and ionospheric monitoring/forecasting is needed?	• Alternate PNT Systems • Tracking Algorithms • Forecast Accuracy and Lead Time • Secondary Users • Mitigation Goals

2. Space Weather and Disturbed Ionospheric Conditions

2.1 Introduction

Terrestrial weather is understood by the public because they experience these conditions as part of their daily lives. But surface weather is not the only type of weather that impacts us every day. According to NASA and the U.S. military, the near-Earth space environment begins at 80 km, while internationally, the lower boundary is defined at 100 km. The upper boundary extends to over 6.6 Earth radii (about 42,000 km) from the center of Earth. "Space weather comprises a set of naturally occurring phenomena that have the potential to adversely affect critical functions, assets, and operations in space and on Earth. Extreme space weather events can degrade or damage critical infrastructures, which may result in direct or cascading failures across key services such as electric power, communications, water supply, healthcare, and transportation." [SWORM, 2019] Specific areas impacted by SpWx include power grid disruptions, radiation hazards, human space exploration, and GNSS and GNSS applications.

The upper atmosphere consists of a mixture of neutral gas and plasma. The region of plasma known as the ionosphere extends from approximately 80 to over 1,000 km above Earth's surface. The ionosphere density varies with altitude and day/night, reaching a maximum density at altitudes ranging between approximately 250 and 500 km. Outside of surface weather, this region has the greatest impact on radio frequency (RF) signals as they propagate into and through this medium. Depending on the frequency of RF signals and the ionospheric structure present, the signal may be refracted, scattered/scintillated, absorbed/attenuated, and/or reflected.

2.2 Space Weather Overview

The largest source of space weather is our sun. The sun, made up of different layers and a strong and variable magnetic field, produces energy through fusion in its core. While the sun's energy is released constantly, it can vary significantly and be associated with various active regions and solar structures. Overall solar activity varies on an approximate 11-year cycle. Figure 1 shows the solar cycles for over 300 years as represented by sunspot number (SSN). During periods of solar cycle maximum conditions, the probability of large solar storms and disturbances is increased. It is these large and variable energy releases that can drive some of Earth's most severe SpWx. Two phenomena that can produce intense energy releases are solar flares and coronal mass ejections (CME).

Solar flares are the largest explosive events in the solar system. They result from the complex interaction of pairs of sunspots and the strong, twisted magnetic fields between the two that release short but intense bursts of energy. These energy releases are in the form of radiation (e.g., radio waves, visible light, X-rays, and gamma rays) traveling at the speed of light and more slowly traveling charged particles (plasma). Solar flares are classified based on the amount of X-ray energy released and are labeled A-, B-, C-, M-, and X-class. With regard to flares, SpWx is driven primarily by C-, M-, and X-class flares. The severest type of flare, X-Class, happens infrequently. The largest recorded X-Flare (X28) occurred on November 3, 2003, impacting a number of technology systems. SpWx impacts during the late October and November 2003 time period resulted from a number of solar flares, solar particle events, and geomagnetic storms. Some of the detrimental impacts and anomalies experienced by technological systems from these SpWx events include the loss of Japan's Midori II satellite, greater than 100 m errors on the FAA Wide Area Augmentation System (WAAS) system, electric power service failure in Malmö Sweden, and the interruption of satellite communications [Evans et al., 2004].

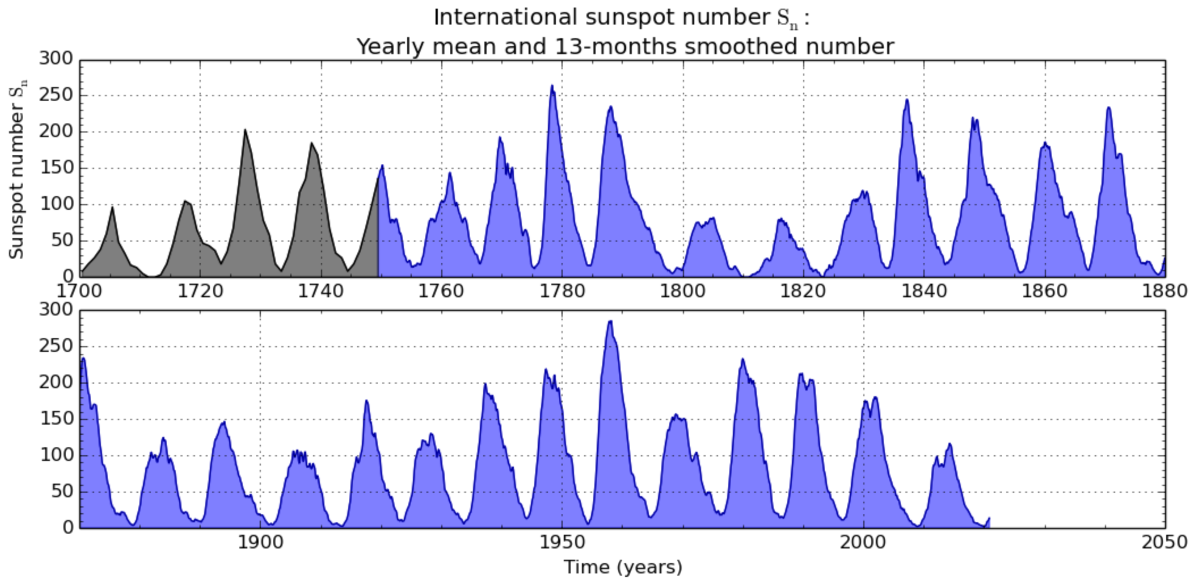

Figure 1. Historical record of sunspot number up to June 1, 2021. Image shows the average SSN until 1749 (black) and the 13-month smoothed SSN (blue). [*Courtesy of SILSO graphics – Royal Observatory of Belgium, http://sidc.be./silso*]

The other type of intense energy releases, CME's, consist of massive high-density bubbles of plasma containing a billion tons of material. These events occur a few times per week during solar minimum to a few per day at peak solar activity. It takes approximately 1–5 days following eruption for the CME to reach Earth, providing time to issue alerts to technology users, although predictive skill on the exact timing and intensity of storming still carries a large degree of uncertainty. While Earth's magnetic field provides some protection, deflecting the solar wind and CME material, enough solar wind energy enters the near-Earth space environment through interactions between the solar wind and Earth's magnetic field to produce geomagnetic storms, effects on Earth's radiation belts, and visible aurora displays that in turn produce a variety of SpWx effects.

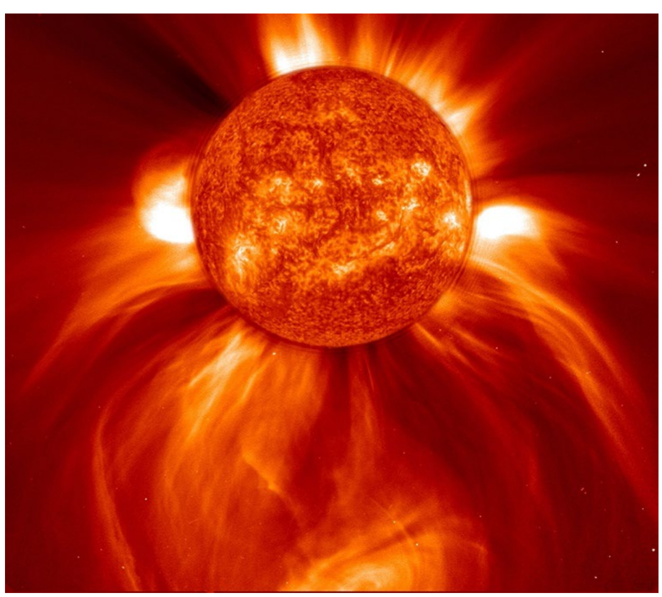

Figure 2. Image from SOHO satellite's coronagraph and EUV imaging telescope showing a CME release on 8 January 2002. *Credit: NASA*

The ionospheric region can be considered a bridge between low-altitude weather and high-altitude SpWx. In addition to geomagnetic storms, with associated currents and particle precipitation driving ionospheric SpWx, waves in the surface neutral atmosphere created by frontal systems, orographic features, etc. propagate to ionospheric altitudes. There they interact with the plasma, seeding ionospheric disturbances. Ionospheric SpWx can be described as any disturbance that causes a significant change in density, composition, or motion of the plasma.

Ionospheric SpWx can adversely impact RF signals, including GNSS, high frequency (HF) communications, and ground radars. GNSS signals are disrupted through large changes, both enhancements and depletions, in density over small horizontal distance (e.g., density gradients, bubbles) and by very small scale and large chaotic density changes (i.e., turbulence).

Large density gradients occur at low magnetic latitudes associated with nighttime density depletions, or bubbles. Often referred to as equatorial bubbles, they can occur at any time of night, but are most frequently observed pre-midnight. At mid-latitudes, large density gradients are associated with wave-like Travelling Ionospheric Disturbances (TIDs). The wavelengths and relative density difference between TIDs' peaks/troughs may produce some GNSS degradation on individual signals, but is highly unlikely to cause any outage. Ionospheric-produced scintillation may impact either the amplitude or phase portion of RF signals, or both. Amplitude scintillation appears more intense at low-magnetic latitudes. It typically occurs along the edges of equatorial bubbles and, because of the typical bubble structure, are narrow, elongated regions. Phase scintillation is more intense at high latitudes.

Another type of SpWx event impacting the ionosphere is the solar radio burst (SRB). Because SRBs are mostly associated with solar flares, the ionospheric effects are only experienced on Earth's dayside. The X6 Flare on December 6, 2006, produced the largest recorded SRB, resulting in GPS receivers losing tracking for approximately five minutes.

2.3 Forecasts and Nowcasts

NOAA's Space Weather Prediction Center (SWPC), located in Boulder, Colorado, has provided the public routine SpWx forecasts since 1965. The center's typical operations staff consists of 12 forecasters, 2 space scientists, and an operations center lead. SWPC operates 24/7 year-round, with typical staffing of two on-duty forecasters with additional surge capability. In addition to forecasts, SWPC provides near-Earth space and solar environment surveillance, data, models, and products.

SWPC publishes forecasts for a variety of parameters related to solar activity. However, three main SpWx events for which SWPC publishes Watches, Warnings, and Alerts are: geomagnetic storms, solar radiation storms, and radio blackouts. The forecasts are described by intensity levels ranging from 1 to 5 (i.e., G.1-G.5, S.1-S.5, R.1-R.5). Each intensity level maps to effects experienced by the most impacted technology or application. Table 4 summarizers the occurrence frequency of each type of SpWx event as a function of intensity level.

Table 4. Occurrence of Space Weather Events in Terms of the Forecast Scales.
(*From https://www.swpc.noaa.gov/noaa-scales-explanation*)

Scale	**Average Frequency (over an 11-year solar cycle)**		
	Geomagnetic Storms	**Solar Radiation Storms**	**Radio Blackouts**
5	4 (4 days/cycle)	<1	<1
4	100 (60 days/cycle	3	8 (8 days/cycle)
3	200 (130 days/cycle)	10	175 (140 days/cycle)
2	600 (360 days/cycle)	25	350 (300 days/cycle)
1	1700 (900 days/cycle)	50	2000 (950 days/cycle)

Forecasts and advisories are disseminated in several ways. Besides the website (https://www.swpc.noaa.gov/) and social media (i.e., Facebook), SWPC provides a no-cost publicly available email-based subscription service. Additionally, dashboards for specific applications, such as aviation, GPS, and electric power, have been developed and are publicly available through the main website.

3. Precision Agriculture

3.1 Introduction

Precision Agriculture (PA) is defined as the "*management strategy that gathers, processes, and analyzes temporal, spatial, and individual data and combines it with other information to support management decisions according to estimated variability for improved resource use efficiency, productivity, quality, profitability, and sustainability of agricultural production"* (*from International Society of Precision Agriculture, https://www.ispag.org/about/definition*). Other organizations have presented similar definitions (e.g., National Research Council, 1997). In the early 1990s, agricultural activities began utilizing GPS position, navigation, and timing (PNT) data, with one of the first applications being yield monitoring. Over almost the next 30 years, GPS PNT use steadily increased until it became a critical part of precision agriculture, enabling 24/7 operations in challenging environments, such as low visibility. It plays an important part in the entire agricultural production cycle: field preparation, planting or seeding, management/application (e.g., water, fertilizer), and harvest. PA technology includes autonomous vehicle navigation (e.g., ground equipment, UAVs), location dependent disbursement (e.g., variable sprayer flow, seeding), and crop/land monitoring/mapping (e.g., soil moisture). Table 5 provides specific PA activities and some of the known benefits.

Different activities require different levels of PNT accuracy. These can be broken down into three categories [Stombaugh, 2018]: low, medium, and high accuracy. Low accuracy, typically meter level, can support activities such as scouting, soil sampling, and field area determination. Medium accuracy, typically sub-meter, can be used for mapping, yield monitoring, and basic guidance operations with larger tillage, spraying, or fertilizing equipment. High accuracy, typically one to a few centimeters, is needed for row crop planting and other precision guidance and machine control operations, such as control of individual planter row units.

Table 5. Specific PA Activities and Associated Benefits Enabled by Highly Automated and Autonomous Systems
(Adapted from Table 4 of FCC Task Force Interim Report [2020c])

Activity	Benefit
Weed from plant ID and herbicide actuation on weeds only	• 50%-90% reduction in herbicide usage • Reduced environmental impact footprint
Nitrogen levels in crops	• Improved yields/output • Optimization of nitrogen use • Improved nitrogen management practices
Early pest and disease ID and actuation	• Improved yields/output • Reduced use of crop protection products • Improved application precision of protection products
Autonomous operations	• Supplements limited availability of skilled labor • Enables 24/7 operations
Self-optimization of equipment systems	• Reduce need for highly skilled labor in difficult environments • Minimizes downtime associated with equipment maintenance
Phenotyping of livestock and crops	• Improves resiliency of next generation breeding processes focused on adaptation to changes in environmental conditions

3.2 PA Navigation Technology

PA navigation technology (NT) has evolved over the years from lightbar driver assist systems to high-accuracy driverless systems. Lightbar refers to a system consisting of a GPS receiver that assists a driver by providing a visual guide, day or night, to steer the equipment along an imaginary reference line. The GPS PNT systems underlying this evolution have also improved over time. Current types of GPS PNT technology include single- and dual-frequency RTK, and single- and dual-frequency PPP. Multi-frequency PPP systems utilizing non-GPS constellations are under development. Alternate navigation technologies include sensor fusion systems that blend data from several sensors (e.g., RF ranging, visual odometer, wheel speed sensors, and IMU) in addition to GNSS PNT, and non-navigation guidance technology (e.g., John Deere's RowSense™).

3.2.1 Real Time Kinematic (RTK) Positioning

RTK positioning systems consist of antenna/receiver units located on individual vehicles (mobile units) and a reference base station. Either the customer's or dealer's semipermanent base station is placed at a known surveyed position so that the range measurements from the GPS satellites expected for that position can be compared to those obtained through actual received GPS signals. Unlike more traditional differential GPS (DGPS) positioning that use range errors (corrections), RTK achieves high accuracy by sending signal phase measurements, in addition to code timing information in the correction message(s), to each mobile unit in real time. The combination of the various error sources results in an approximate 1 ppm error with a given baseline length.

Early lightbar guidance systems used single-frequency RTK positioning enabling 4–30 cm accuracy [Takasu and Yasuda, 2008]. A fully automated guidance (AG) system with single-frequency RTK is capable of 17 cm accuracy. These accuracy levels translate to the need to have swath overlap, which will increase field inputs and may reduce the overall profitability of a field. Newer systems employ multi-frequency and multi-constellation tracking, which improves the horizontal accuracy to below 2.5 cm [SEESAW-II Day 1, S. Rounds].

RTK positioning has some limitations and is susceptible to ionospheric conditions. First, the number of base stations and the separation distance to the mobile units are limited to approximately 25–50 km. One factor limiting the separation distance for single-frequency RTK is the potential ionospheric density gradients differing between the base station location and the mobile units that exist during a during a disturbed or active ionospheric period. These conditions can result in spatial decorrelation and cycle slips that lead to loss of RTK. These issues are mitigated by using dual-frequency RTK, which removes the ionosphere error source by taking advantage of the fact that the ionosphere is dispersive with respect to frequency. An additional issue for single-frequency receivers is that they rely on broadcasted ionospheric models that only compensate for about 50% of the induced ionospheric error. Another factor that affects both single- and dual-frequency RTK systems is troposphere error. The difference is that tropospheric conditions seen by the base station and the mobile units limits the separation distance. Single-frequency RTK systems are more likely to experience outages due to ionospheric scintillation conditions.

3.2.2 Precise Point Positioning (PPP)

The most recently widely deployed PA operational systems utilize the Precise Point Positioning (PPP) technique. Systems utilizing PPP do not require individual base stations at each end user's operation, but instead utilize sparse global networks of satellite tracking stations to estimate precise satellite orbit, clock corrections, biases, and ionospheric corrections based on a global model. These corrections are then transmitted to the end users' systems, via the internet or satellite up/downlink (L-Band), which then incorporates them into the local navigation solution.

In general, the PPP technique is more resilient to day-to-day ionospheric conditions. Initially, an individual receiver's operation begins by obtaining an initial position solution using a dual-frequency code point solution. The accuracy of this initial solution is tens of centimeters and takes only a few minutes at most. Following a "convergence" that could take up to 20 minutes, the transmitted corrections are applied, resulting in centimeter-level accuracy that is maintained through the subsequent operation. Ionospheric conditions that degrade the usability of the available signals may significantly delay or prevent convergence. However, once convergence is obtained, unless tracking is completely lost, the transmitted corrections allow the system to continue to operate. Intense ionospheric scintillation events prevent signal lock and tracking, resulting in a complete outage of the local system. Unlike RTK, PPP is not affected by spatial decorrelation. The main disadvantage is that PPP signals come from single satellites, although it can be provided through other systems such as Networked Transport of Radio Technical Commission for Maritime Services via Internet Protocol (NTRIP). Some examples of PPP systems include Trimble's RTX (over 100 tracking stations), John Deere's StarFire™ Network (over 70 reference stations), NovAtel's CORRECT™, and Fugro's MarineStar for marine applications.

3.2.3 Multi-constellation GNSS Receivers

The importance of GNSS continues to grow and other countries have developed and deployed their own satellite systems. It is becoming more common for GNSS receivers to track multiple constellations in addition to GPS. This capability provides a potential mitigation for ionospheric-driven impacts, especially for ionospheric scintillation common at low latitudes. Ionospheric scintillation occurs in relatively narrow and localized regions. From a ground-receiver perspective, that often results in a portion of the sky being clear of scintillation for a good part of ionospheric scintillation events. Hence, the increased probability of "seeing" more satellites that are evenly distributed throughout the sky outside of scintillation regions is advantageous to all PA systems. The adoption of multi-constellation receivers capable of simultaneously tracking satellites from multiple GNSS constellations should help in mitigating the impact of ionospheric disturbances and the recovery from their effects.

3.3 Ionospheric Induced Anomalies

Presentations and discussions during SEESAW-II described how observed ionospheric impacts on GNSS PA systems manifest as deep fades resulting in cycle slips and loss of signal lock. While both ionospheric scintillation structures and large density gradients can produce these effects, it is ionospheric scintillation structures that are most frequently encountered. As expected, ionospheric impacts vary around the globe. The continental US (CONUS) has observed very few instances of scintillation on commercial systems, and then only during development and testing. There have been few PA issues reported in CONUS that can be attributed to ionospheric conditions. This may be due to a lack of reporting or issue recognition. Ionospheric scintillation induced issues are common in Brazil due to the combination of its low-magnetic latitude location and increasing adoption of PA.

There are several potential technology mitigations that can be employed to improve the operability during mild to moderate ionospheric scintillation conditions. These include adoption of multi-constellation GNSS measurements, improved tracking of weak signals due to ionospheric induced fading, enhanced cycle slip detection, faster reacquisition of lost signals through adaptive tracking loops, and identification of individually impacted signals and removal from navigation calculation.

3.4 Disruption Reporting

GPS disruption reporting is a very important part to connecting the different communities. Frequent and meaningful disruption reporting can provide invaluable insights into the scope and impacts of the problem. In the U.S., civil GPS disruption reporting is handled by two organizations based on the operational domain of the user. The U.S. Department of Homeland Security, U.S. Coast Guard Navigation Center (NAVCEN) handles civil, non-aviation disruption reporting, and the U.S. Department of Transportation, Federal Aviation Administration (FAA) handles civil, aviation-disruption reporting for U.S. airspace.

Precision agriculture can involve both terrestrial and aviation equipment. As pointed out in this report, various field equipment, such as tractors, often rely on GPS for precision position, navigation, and timing data. Furthermore, both crewed aircraft and uncrewed aerial systems (UAS) are used for various applications, such as aerial spraying of pesticides or fertilizer, surveying, and crop monitoring. Due to this dichotomy of precision agriculture user equipment, both reporting channels apply.

NAVCEN is located in Alexandria, Virginia, and provides various navigation system services for both maritime and terrestrial GPS users. Currently, this includes any on-orbit spaceborne GPS receivers, which could include systems such as StarFire; GPS is just one of the information services it provides. The public website, shown in Figure 3, includes the following current, authoritative, and traceable resources:

1. GPS constellation status: This includes orbital slot, pseudorandom number or code assignment (PRN), operational atomic frequency standard type, and any outage information from notice advisories to NAVSTAR users (also called a NANU).

2. Approved GPS testing events: This is a daily list of times, locations, and affected areas of approved GPS testing events that often involve interference that can disrupt GPS use. Archives of previous reports are not available on the public website.

3. GPS almanacs: This includes GPS satellite status and operational advisory messages in several standard formats.

4. GPS disruption or problem reports: This includes both the status of previous GPS problem reports (https://navcen.uscg.gov/?Do=GPSReportStatus) and a web form to report a new civil, non-aviation GPS disruption (https://navcen.uscg.gov/?pageName=gpsUserInput).

5. Various other GPS information links: This includes various authoritative GPS technical references, such as GPS.gov and links to NOAA's Space Weather Predication Center's GPS Community Dashboard.

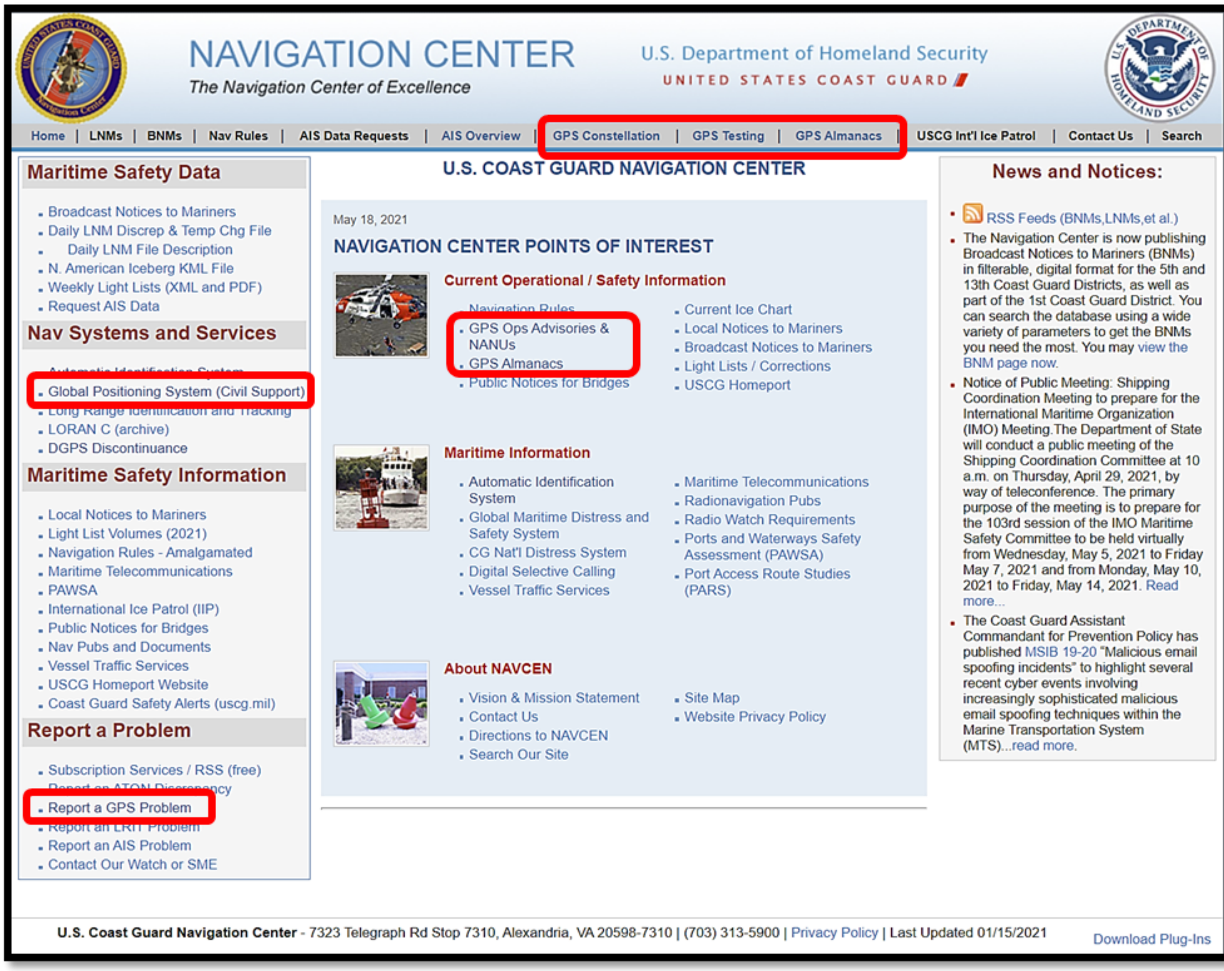

Figure 3. NAVCEN Website (https://www.navcen.uscg.gov/).

The FAA has distributed centers that provide airspace monitoring and situational awareness and navigation services. The FAA also operates WAAS, a space-based augmentation system (SBAS) for GPS. WAAS provides integrity monitoring and atmospheric correction services through a one-way satellite broadcast service for WAAS-equipped GPS receivers or user equipment. WAAS uses a network of over 40 fixed, high-grade GPS receivers or WAAS reference stations (WRS). The FAA's website has many different advisory tools available that display GPS-related systems information such as receiver autonomous integrity monitor (RAIM), automatic data systems-broadcast (ADS-B), WAAS, and Notices to Airmen (NOTAMs). There is also a GPS anomaly reporting [web] form for civil and aviation GPS disruptions in U.S. airspace (see Figure 4).

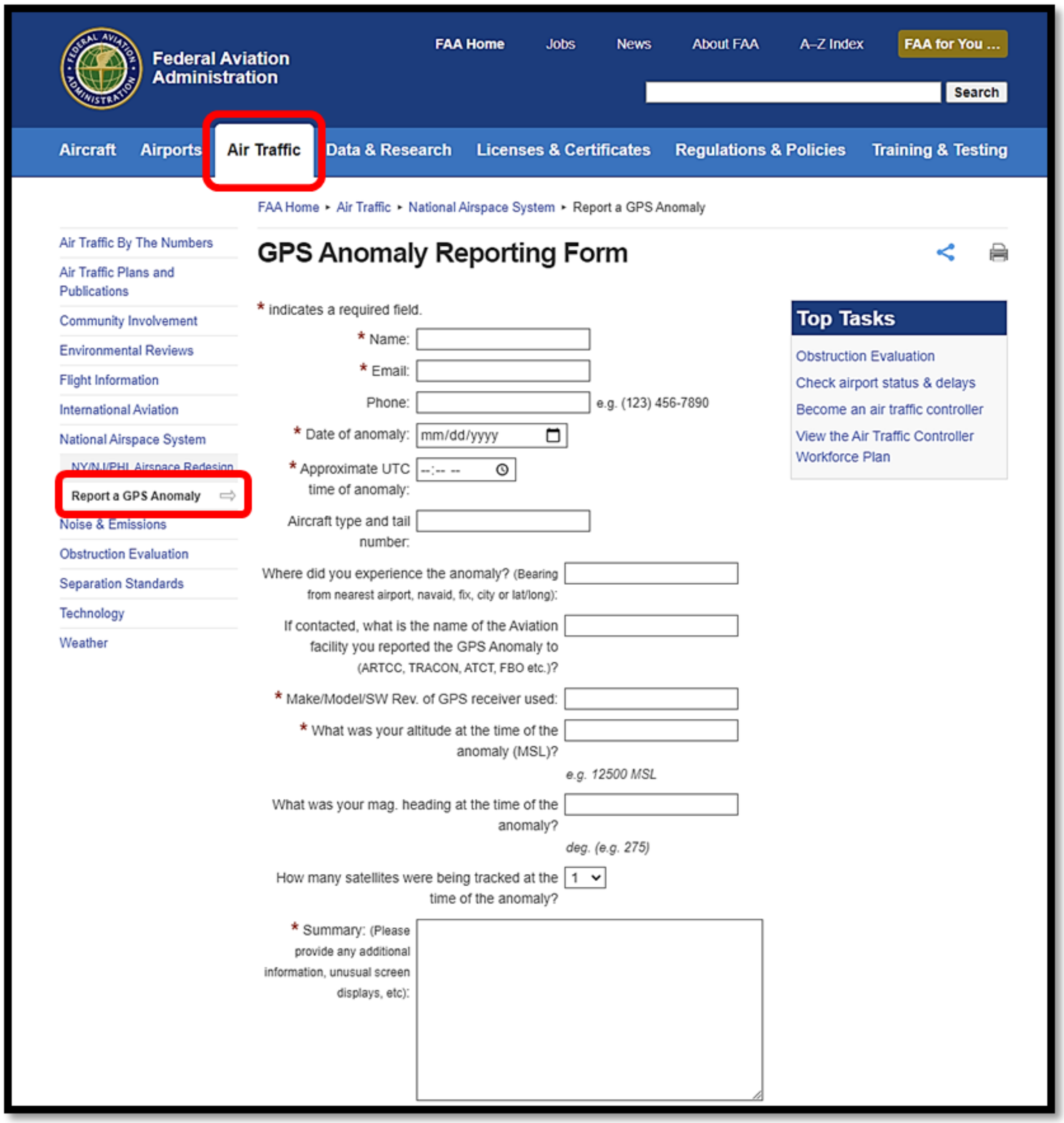

Figure 4. FAA website (https://www.faa.gov).

Per the 2017 interagency memorandum of agreement with respect to support of users of the NAVSTAR GPS, the NAVCEN and the FAA work in conjunction with the U.S. Space Force, which owns and operates GPS, to ensure reported service interruptions are addressed. Our inspection of the historical GPS problem reports available on NAVCEN's public website showed only two out of over 425 reports from 2017 to 2021 were related to [precision] agriculture. GPS disruption reporting is very important for determining attribution of disruption sources and informing the development of more resilient, future precision agriculture and other GNSS or GPS user equipment.

4. Economic and Societal Impacts

4.1 Direct Technology Adoption

The adoption of GNSS technology to fine-tune agricultural field operations over the last three decades has been unprecedented relative to other agricultural innovations during the period. Figure 5 shows the commercialization dates for a subset of precision agricultural technologies, including those relying on GNSS. As agricultural machinery sizes increased, field operations became much more precise due to the synergistic relationship between farm machinery and GNSS-enabled NT. The farm-level benefits of GNSS guidance, including efficient operations planning and reduced labor hours for the same-sized area, are well understood.

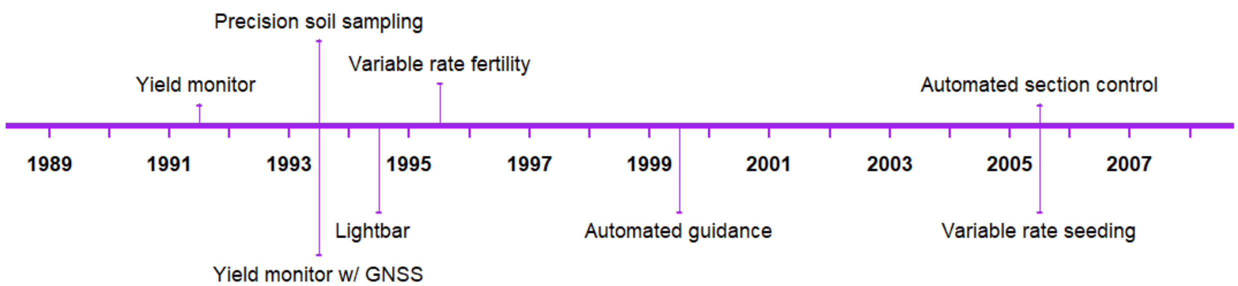

Figure 5. Commercialization dates of select precision agricultural technologies.

As AG has become prevalent and many of the implements used on US farms have gotten wider, newer farm machinery has been reconfigured because visual marker (VM) guidance is no longer needed. For example, AG has facilitated wider crop planters while allowing manufacturers to remove the expensive row markers used for VM guidance. Within a decade of introducing AG as original equipment manufacturer (OEM), one manufacturer introduced a 120-foot-wide planter. Because many planters no longer have visual row markers, it may be necessary to pause planting operations during a GNSS outage. Analogies for over-90-foot-wide sprayers and other input applicators could also be made, given that many current machines are not equipped with foam or other VM systems because farm equipment operators rely on GNSS for lightbar or AG.

4.2 Societal Impacts and Secondary Markets

In addition to improvement in yield and efficiency, PA through GNSS also provides significant quality-of-life improvements for those employed in the agriculture area. For example, fewer equipment operators are needed, and those operators can complete the work in less time and without the additional physical stress of operating the equipment. Besides growing crops, GNSS technology can assist in other aspects of agriculture. For example, cattle are now being equipped with GNSS receivers on collars to enable ranchers to manage the livestock utilizing virtual fences. With a single click of a mouse, they are able to adjust virtual fences and move the herd slowly without the need for personnel on the range manipulating gates and moving the animals. Further, virtual fences in place of the more traditional fencing prevent unintentional impacts on the area's wildlife and environment.

Besides directly assisting in the physical activities related to crop growth cycles, GNSS is used to geolocate various parameters associated with yield production. This data is of significant interest to a variety of groups, including commodities markets, data analytics companies, and governmental regulatory divisions. For example, participation in federal subsidy programs may require sufficient georeferenced farm data to determine the eligibility of a particular farm/crop. Sustainability metrics from USDA

National Resource Conservation Service (NRCS) may not be able to be calculated in absence of precision agriculture data such that the farm operator may not qualify for anticipated cost sharing or other subsidy programs. Thus, lack of farm data to support farm management decision-making or participation in “big data” opportunities may have lingering impacts on farm profitability. Therefore, the use of precision technology and the associated collected data are essential to farmers considering the best use of precision technology, agricultural industry marketing the technology, university researchers searching for optimal management of technology, and agricultural and international policy makers.

4.3 Impact Example: Midwest Corn Production

It is important to understand that agriculture is subject to annual biological cycles and weather events. An outage of GNSS would have different effects on agriculture depending on what time of year the event occurred. While a GNSS outage during harvest may not stop harvest operations, the georeferenced yield data will not be collected, which could impact next-year planning, as well eligibility for various programs. An outage occurring during spraying time or planting time may result in the operator opting to not continue activity due to lack of guidance, especially if VM guidance alternatives are not available, having a much greater impact on the final yield.

As an example, typical corn production processes and activities in Kansas are presented in Figure 6. Planting typically occurs in April and May such that a GNSS outage for a few days during those weeks of the year would impact farmers’ ability to plant seed into the soil; however, harvest activities would not be impacted. Likewise, if a GNSS outage occurred on October 1, harvest would likely continue but without the ability to geo-reference data from yield monitors or other harvest sensors. Thus, the economic impact of either an intermittent or extended GNSS outage could range significantly by region, crop, and time of year.

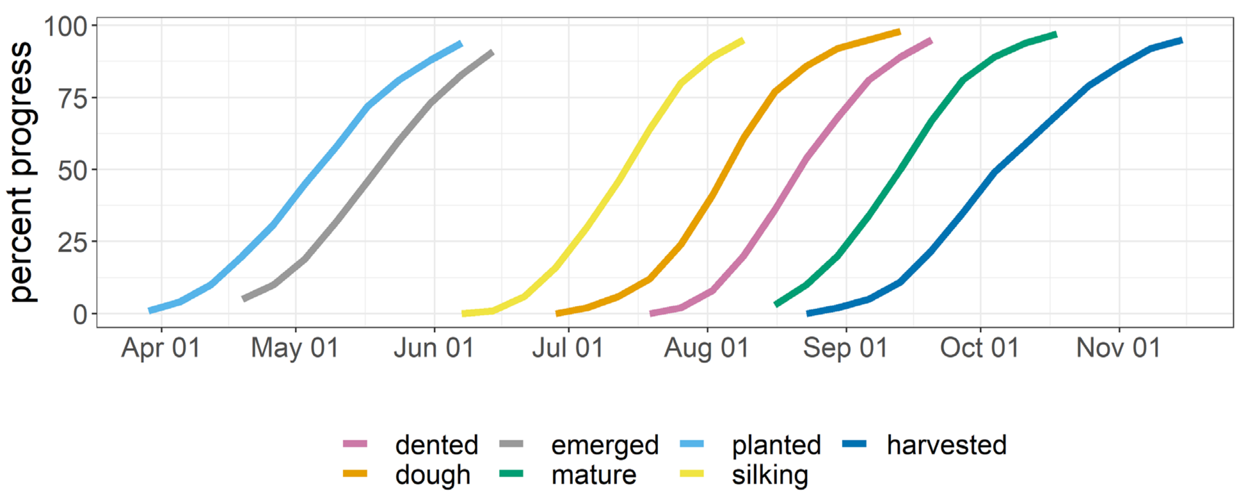

Figure 6. Typical annual progress of select corn production activities in Kansas. (*Source: USDA NASS*)

Since becoming operational for civilian agricultural uses, GNSS has not fallen below performance standards. However, substandard performance may occur from either manmade (e.g., local interference) or natural sources (e.g., ionosphere anomalies, SpWx events). Other plausible causes of an agricultural GNSS outage include correction services embedded as part of the agricultural systems going off-line, such as failure to renew subscription services.

While farm-level economic value of GNSS guidance has been reported [Griffin et al., 2005b], no studies have estimated the regional benefit of the technology to production agriculture or, conversely, the cost of either the technology suddenly becoming unavailable for a specific period or degradation in reliability. However, the aggregate costs of a GNSS outage can be estimated based on changes in input uses and crop production within the farm gates. Although the absence of GNSS capability may only impact production efficiency rather than ceasing production, at least in the early years of AG, the cost of inputs and reduced yield may be substantial.

To give some insight into regional impacts from a period of complete GNSS outage, example loss was estimated using 2004 data. Note that while a complete outage is unlikely in CONUS, the estimate provides a worst-case order of magnitude estimate of the impact. The estimates presented here are part of a more detailed study [See Appendix B] and utilize the most recent GNSS guidance technology adoption statistics, including farm-level and service-provider adoption statistics from the USDA Agricultural Resource Management Survey (ARMS) and the annual CropLife/Purdue University Precision Agriculture Survey, respectively.

Utilizing a mathematical linear programming model, the realized gains for a single representative-sized 1,214-hectare U.S. Corn Belt farm was estimated [Griffin et al., 2005a]. In the 2005 study, several scenarios ranging from VM reference to GNSS NT at several accuracies were compared. Table 6 illustrates the gains achievable in terms of dollars gained through improved equipment efficiency (working rate) using AG, achieving accuracies at the 1 decimeter (dm) and RTK levels, increased hours of equipment operation, and the additional amount of land that could be farmed for the given level or equipment and time. While modest, the additional value gained through the use of GNSS-enabled systems could make the difference between a successful land rental bid and being left behind in the competitive Corn Belt market for farmland.

Table 6. Change in Returns and Planter Capacity Utilization Relative to a Base Farm Value of $1,452,173 in 2004 USD

GNSS NT	Contribution Margin (US$ Farm^{-1}) for 2004 USD		
	Increased Working Rate ($)	Increased Equipment Hours ($)	Increased Farm Size ($)
1 dm AG	36,773	57,802	387,360
RTK AG	37,364	57,802	389,062

Regional costs of GNSS outage can be estimated by a simple summation of the farm-level losses for all affected farms and can be as complex as including other direct and indirect economic impacts using community analysis methodology. Assumptions concerning the number of farmers making use of GNSS and the value of production for the average farm must be made. The USDA 2002 Census of Agriculture [Dept. Ag., 2004-2006] states that there were 26,900 farms in Illinois, Indiana, Iowa, and Ohio, all in the North Central Region of the U.S., that have more than $500 in annual sales. According to estimates from Schimmelpfennig and Lowenberg-DeBoer (2020), 70% of farms use AG technology. Using farm-level values of GNSS-enabled navigation technologies (See Appendix B), the regional economic loss due to a GNSS outage at the technology adoption rates in 2004 can be roughly estimated as presented in Table 7. Note the regional loss is roughly the same for either 1 dm accuracy or RTK AG for a given initial farm value. With inflation and growth in technology use, the loss could easily exceed billions of dollars. The values are the worst case for an extended loss of GNSS use regardless of the outage source. Ionospheric events capable of disrupting GNSS PA technology over CONUS are rare during quiet solar conditions and are likely to be infrequent during solar maximum, as well as being fairly short in duration. Thus, any regional losses due to ionospheric-associated SpWx is estimated to be at most a couple of percent of the overall loss per a single regional crop (around tens of millions of dollars annually).

Table 7. Estimate of Regional Farm-Level Costs due to a GNSS Extended Outage. For Corn Production.*

GNSS-NT	Farm Value of GNSS-NT	Farms with GNSS-NT (%)	Farms Affected	Regional Loss (USD$)
1 dm AG	57,802	70	18,830	$1,088,411,660
RTK AG	57,802	70	18,830	$1,088,411,660

*Note, the impact due to ionospheric induced outages for CONUS is likely on average less than a few percent.

5. Bridging the Gap – Future Needs

Ultimately, the use of PA enables the agriculture community to increase the realized crop yield by improving efficiency of all field activities from planting through harvesting. As shown in Figure 7, PA reduces the yield gap resulting from management inefficiencies and weather impacts. Thus, any interruption or degradation of GNSS PNT reduces the potential yield gain that may have been realized. In the worst-case scenario, the complete loss of PA would reduce the yield 15%–30%. However, as ionospheric impacts do not generally cause complete loss of PNT capabilities over the annual production cycle of a field, the impact of ionospheric impacts are more likely to be a few percent of yield loss. While small, it could be the difference between profit and loss for smaller operators, especially in years with more adverse economic conditions.

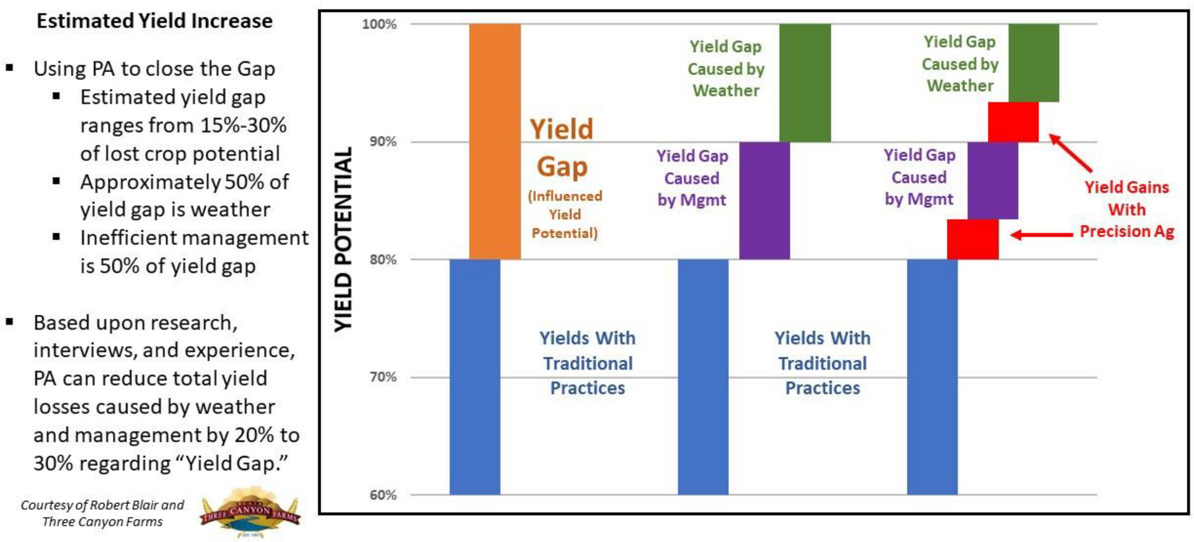

Figure 7. Illustration of PA impact relative to overall potential yield.
(Adapted from FCC Encouraging PA Adoption Report [2020d])

Three types of users within the PA community have been identified that may be impacted by SpWx forecasts: (1) technology and system developers, (2) farm operators and owners, (3) secondary users of aggregated farming data. Each of these users experience differing levels of effects due to ionospheric impacts. As discussed earlier, current PA PNT systems are fairly robust to the majority of day-to-day ionospheric conditions experienced over the last decade. However, extreme conditions, as well as low-latitude scintillation, remain issues that require improved mitigation techniques. Currently, on-site farmers located at low latitudes experience significant impacts resulting from PNT outage due to ionospheric scintillation. Finally, as the aggregated farming data is collected and exploited, the inclusion of SpWx data and its implication on the farming data may be of increasing importance, although relatively less than other non-SpWx correlation factors.

Over the course of the two-day SEESAW-II discussions, several key observations emerged related to current and future challenges of ionospheric disruptions and impacts on PA. These observations are presented below in context of future needs along with potential work/strategies, as appropriate, to begin to address them.

5.1 *Observation 1*: The Determination of Signal Disruption Sources is Key for Real-time Operations and Future Technology/System Developments

There are many interference sources that can degrade the performance of PA systems besides SpWx. These include multi-path signal scattering effects from sources like trees on the edges of fields, orchard canopies, nearby large structures, fading due to atmospheric moisture (e.g., rain, dense clouds), and inadvertent jamming/interference from terrestrial manmade sources as well as deliberate, but currently unlikely, spoofing and jamming. Typically, the ionospheric impacts observed by PA systems are mostly limited to deep signal fades or complete loss of signal lock. By understanding the characteristics of interference sources, enabling identification provides several potential mitigation options, such as removal of individual signals or all signals from a particular portion of the sky experiencing ionospheric scintillation from the navigation solution calculation, removal or relocation of trees or structures, modification of other nearby ground transmissions or blockers, or limited rescheduling of activities.

Strategy 1**:** *Encourage research in the characterizing of degraded signals resulting from differing terrestrial and space-based sources with the goal of developing algorithms or other techniques capable of determining the type of interference sources in near-time.*

5.2 *Observation 2:* Multi-frequency GNSS Systems Will Likely Mitigate the Day-to-Day Quiet and Moderately Disturbed Ionospheric Variability Impacts on PA End Users

Navigation systems for PA are moving toward utilizing all available GNSS signals. Currently, GPS and Galileo tracking are common in new systems. Within the next several years, utilization of the frequencies from other GNSS constellations (e.g., GLONASS, BeiDou, QZSS, IRNSS) is expected. However, the actual adoption and deployment of multi-frequency GNSS systems will lag due to slow replacement of established legacy systems in use by farms. Because of that lag, a significant number of single-frequency and RTK systems remain in operation. In general, ionospheric impacts on PA outside of the low latitudes may have been minimal partially due to the relatively quiet SpWx conditions of the last 11-year solar cycle. While single frequency and RTK systems are more susceptible, the newer multi-frequency multi-constellation RTK and PPP technologies have not been fully deployed to enable understanding of performance during a period of increased solar activity or ionospheric disturbances outside of the low latitudes.

Solar cycle maximum conditions over the next decade mean a higher probability for strongly disturbed ionospheric conditions to occur. Large geomagnetic storms can result in scintillation and intense plasma gradients outside of low-geomagnetic latitudes. There is a dearth of multi-frequency PA system performance data obtained during intensely disturbed ionospheric condition due to the last solar maximum occurring prior to multi-frequency systems and overall PA adoption. Thus, it is not currently feasible to fully determine the susceptibility of either legacy, currently deployed, or next generation multi-frequency systems to more frequently disturbed ionospheric conditions at all latitudes.

Strategy 2: *Perform assessments to determine the impacts on multi-frequency GNSS systems due to disturbed ionospheric conditions that are more likely to be observed during the upcoming solar maximum period.*

5.3 *Observation 3:* Ionospheric Nowcasts of Ionospheric Conditions Indicative of Signal Degradation or Loss of Lock Would Enable Performance Improvements to PA Navigation Systems

Currently, low-latitude amplitude scintillation has the largest effects on PA and manifests as deep fades and complete loss of signal lock. As mentioned previously, ionospheric scintillation effects increase with decreasing signal frequency. Because the current GNSS constellations transmit in the L-Band, it is likely that if ionospheric scintillation structures are present, the majority of the signals traversing the structures are likely to be scintillated.

As previously described, the ionospheric density structures causing scintillated signals occur on the edge of bubbles. These bubbles drift and thus, the regions of scintillation drift as well. Further, several bubbles can occur one after another and scintillation can drift in and out of a system's field of view (FOV). While the number of signals within the FOV of the PA systems will increase multi-fold in coming years with utilization of multi-frequency GNSS, scintillation will continue to be an issue at low latitudes. One mitigation strategy from the technology developers' perspective is to remove signals that are being degraded due to ionospheric scintillation from the internal navigation solution algorithm. Nowcasts could enable PA systems to be more robust and continue farming activities during mild and moderate scintillation conditions. Ideally, a nowcast that indicates whether individual signals are passing through scintillation as observed at a given ground location would be preferred. However, that is most likely unrealistic due to the large number of ground sites and signal orientations. A nowcast that provides the PA systems' regions of the sky with structures that may scintillate signals is more feasible (i.e., regional nowcasts). Then the individual systems can calculate whether a given signal would pass through the suspect region using the elevation/azimuth of the GNSS satellite and determine whether to use it further in their navigation algorithms.

Strategy 3a: *Develop and/or improve a publicly available ionospheric scintillation nowcast for low-latitude regions.*

Ionospheric scintillation forecasts would provide the most benefit to on-site agriculture operators and researchers. Forecasts ranging from six hours to a week would provide different levels of benefits to operators. These forecasts would be analogous to a rain forecast allowing operators to more efficiently plan activities and stage equipment and personnel. For low latitudes where scintillation can occur nightly during parts of the year, knowing when a possible clearing of scintillation conditions could occur would greatly assist in reducing the yield gap (See Figure 7).

Strategy 3b: *Develop and distribute forecasts ranging from six hours to weekly that provide an overall probability of scintillation occurrence with focused forecasts of likely minimal scintillation conditions.*

5.4 *Observation 4*: The Most Significant Economic Impacts due to Ionospheric Conditions Occur at Low Latitudes Where Intense, More Frequent Ionospheric Scintillation Occurs

In the last few years, several governmental agencies, such as the Department of Transportation, USDA, and the FCC have indicated the importance of robust GNSS systems to the nation's infrastructure [Hansen et al., 2021 and reference therein] and, in particular, agriculture [USDA Task Force, 2019; FCC Task Force, 2020a, 2020b, 2020c, and 2020d]. In recent years, there has been an increase in the number of reports documenting the financial gains achieved with PA [e.g., FCC Task Force, 2020d and references therein], with the estimated gains of approximately $7.91/acre [SEESAW Day-1, Rounds]. However, there are limited studies of financial cost due to PA degradation or intermittent loss due to specific factors.

Section 4 describes the various economic and societal impacts influenced by the adoption of PA, and an example quantifying the efficiency in terms of operations hours and dollar gains for an individual farm over a corn-growing season in the early days of PA adoption. This was then used to extrapolate the maximum regional loss for a GPS outage period. This example study provides a worst-case example of a GPS outage; it includes use of less robust system technologies (e.g., single-frequency tracking, RTK) and does not break down the impact specifically by the source or duration of the outage period. If SpWx was only responsible for the outage a few percent of the time, it would still equate to tens of millions of dollars for a single crop. The section 4 analysis also assumes that the farmer would have the option of reverting back to previously used navigation techniques such as row markers, foam makers, or other technology considered status quo. However, as the proliferation and reliance of PA systems has become more entrenched, it is unlikely that larger operators have the flexibility or financial capability to ether possess or maintain older technology. Overall, a more detailed economic analysis focusing on PA impacts due to GNSS intermittent loss needs to be performed to truly gauge the potential losses to the agricultural community.

To adequately gauge the significance of ionospheric impacts on PA, a detailed economic analysis utilizing the most current information is needed that specifically looks at the losses during low-latitude scintillation events. In the future, agriculture land usage at higher latitudes, a region that regularly experiences ionospheric phase scintillation, may increase due to changing climate, and any study would benefit from its inclusion. While ionospheric impacts are minimal in the continental United States, such a study would assist in determining the prioritization of scintillation research and forecasting among PA developer and the international SpWx communities.

Strategy 4: *Engage in more focused estimates of the financial impact of the intermittent loss of current GNSS-enabled PA operations at low latitudes and future emerging impacts at high latitudes.*

5.5 *Observation 5*: The Communities Represented at the Workshop Were Generally Unaware of the Available Resources, Data, and Technology Available to Assist in Their Respective Area of Operation and Research

Many of the SEESAW-II attendees expressed strong appreciation for Day 1 of the workshop, which presented the topic from different perspectives. A number of misconceptions came to light that were ultimately corrected. For instance:

1. Geomagnetic storms and extreme events are not limited to solar maximum periods. The probability of occurrence increases during solar maximum.

2. Not all “scintillation” observed by end users are due to ionospheric scintillation. Afternoon signal disruptions as reported by some end users are likely due to other types of ionospheric structures.

3. PPP technology, as well as dual-frequency receivers, do not rely heavily on a receiver-embedded ionospheric model. Thus, improved ionospheric models, for these technologies, are a low priority to the PA developer community.

4. Scintillation occurrence is not directly related to SSN. While SSN is a good indicator of overall solar activity, ionospheric scintillation occurrence is complex and varies as a function of longitude, season, and local conditions as well as solar activity input.

While these points may be obvious to the individual communities, it is only through direct conversations between the communities that improved insight of relevant concepts and technology capabilities can be achieved. In turn, this will spur greater innovation and understanding within each individual community.

Strategy 5: *Continue bridging the communities through discussions like those begun at SEESAW-II through increasing participation in each other’s groups’ respective community newsletters, publications, conferences/workshops, and social media.*

6. References

[1] Boehlje, M.D., and Eidman, V.R. (1984). Farm Management. New York: Wiley.

[2] Dantzig, G.B. (1949). Programming interdependent activities, II, mathematical model, Econometrica, 17: 200-211.

[3] Evans, D. L., C. C. Lautenbacher, R. D. Rosen, D. L. Johnson (2004). Intense Space Weather Storms October 19 – November 07, 2003, *NOAA & Dept. Comm. Service Assessment*, https://www.weather.gov/media/publications/assessments/SWstorms_assessment.pdf.

[4] FCC Task Force for Reviewing the Connectivity and Technology Needs of Precision Agriculture in the United States (2020a). "Accelerating Broadband Deployment on Unserved Agricultural Lands Working Group", *Interim Report*.

[5] FCC Task Force for Reviewing the Connectivity and Technology Needs of Precision Agriculture in the United States (2020b). "Mapping and Analyzing Connectivity on Agricultural Lands Working Group", *Interim Report*.

[6] FCC Task Force for Reviewing the Connectivity and Technology Needs of Precision Agriculture in the United States (2020c). "Examining Current and Future Connectivity Demand for Precision Agriculture", *Interim Report*.

[7] FCC Task Force for Reviewing the Connectivity and Technology Needs of Precision Agriculture in the United States (2020d). "Encouraging Adoption of Precision Agriculture and Availability of High-Quality Jobs on Connected Farms, *Interim Report*.

[8] Griffin, T.W., Lambert, D.M., and Lowenberg-DeBoer, J. (2005a). Economics of Lightbar and Auto-Guidance GPS Navigation Technologies. In Precision Agriculture 2005, J.V. Stafford, ed., pp. 581-87. Wageningen Academic Publishers, Wageningen, Netherlands.

[9] Hansen, A., Mackey, S., Wassaf, H., Shah, V., Wallischeck, E, Scarpone, C., Barzach, M., and Baskerville, E. (2021). Complementary PNT and GPS Backup Technologies Demonstration Report, Sections 1-10, U.S. Department of Transportation: John A. Volpe National Transportations Systems Center., *DOT-VNTSC-20-07*.

[10] Griffin, T. W. (2009). Whole-farm Benefits of GPS-enabled Navigation Technologies, ASABE Annual International Meeting, Reno, Nevada, June 21 – June 24, 2009, Paper Number: 095983.

[11] Griffin, T.W., J. Lowenberg-DeBoer, D.M. Lambert (2005b). Economics of Lightbar and Auto-Guidance GPS Navigation Technologies. In J.V. Stafford (ed.) *Precision agriculture '05*. 5th European Conference on Precision Agriculture, Uppsala, Sweden. pp 581-587.

[12] National Research Council (1997). *Precision Agriculture in the 21st Century: Geospatial and Information Technologies in Crop Management*. National Academies Press. Washington, D.C., http://www.nap.edu/catalog/5491/precision-agriculture-in-the-21st-century-geospatial-and-information-technologies.

[13] Schimmelpfennig, D., and J. Lowenberg-DeBoer (2020). Farm Types and Precision Agriculture Adoption: Crops, Regions, Soil Variability, and Farm Size. Global Institute for Agri-Tech Economics. Working Paper 01-20.

[14] Space Weather Operations, Research, and Mitigation Working (SWORM) (2019). "National Space Weather Strategy and Action Plan", Group National Science & Technology Council.

[15] Stombaugh, T. (2018). Satellite-based positioning systems for precision agriculture. In: Shannon, D.K., Clay, D.E., and Kitchen, N.R. (eds). Precision Agriculture Basics, pp. 25-35. ASA-CSSA-SSSA, Madison, WI.

[16] Takasu, T., and A. Yasuda (2008). Evaluation of RTK-GPS performance with low-cost single-frequency GPS receivers, *Proc. Inter. Symp. GPS/GNSS, http:/isgps2008_paper_ttaka.doc.*

[17] USDA Task Force on Agriculture and Rural Prosperity (2019). A Case for Rural Broadband.

[18] USDA 2002 Census of Agriculture. Volume 3, Special Studies (2004-2006). https://lccn.loc.gov/2009397111.

[19] Griffin, T.W., D. M. Lambert, and J. Lowenberg-DeBoer (2008). Economics of GPS-Enabled Navigation Technologies Navigation Technologies. In Proceedings of the 9th International Conference on Precision Agriculture, Denver, CO July 21-23, 2008.

Appendix A. Acronyms

ADS-B	Automatic Data Systems-Broadcast
AG	Automated Guidance
ARMS	USDA Agricultural Resource Management Survey
FAA	Federal Aviation Administration
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
IMU	Inertial Motion Unit
LB	Lightbar
LP	linear programming
NAVCEN	U.S. Coast Guard Navigation Center
NOTAM	Notices to Airmen
NT	Navigation Technology
NTRIP	Networked Transport of Radio Technical Commission for Maritime Services via Internet Protocol
OEM	Original Equipment Manufacturer
PA	Precision Agriculture
PRN	pseudorandom number or code assignment
RAIM	Receiver Autonomous Integrity Monitor
SBAS	space-based augmentation system
SpWx	Space Weather
UAS	uncrewed aerial systems
VM	visual marker
WAAS	Wide Area Augmentation System
WR	working rates
WRS	WAAS reference stations

Appendix B. Economic Analysis Details

The following economic analysis details build upon previous work of Griffin et al. (2005a and 2005b, 2008) and Griffin (2009) by estimating economic losses of reverting from GNSS-enabled NTs back to visual marker systems. By summing the estimated farm-level value of adopting GNSS NTs for an existing farm across a region, a proxy for the cost of a regional GNSS outage was determined.

B.1. Methodology

To address the economic feasibility of GNSS NTs, Griffin et al. (2005a) formulated a mathematical linear programming (LP) model for a representative-sized 1,214-hectare U.S. Corn Belt farm. Several scenarios were compared: (1) a baseline scenario with foam, disk, or other visual marker reference without GNSS navigation; (2) LB navigation with basic ±3 dm accuracy; (3) AG with satellite subscription correction; and (4) AG with a base station (RTK) and ±1 cm accuracy. Evaluation of whole-farm returns over incremental management scenarios builds upon previous research by evaluating the changes to inputs costs.

Linear programming has been utilized to determine optimal solutions to contribution margins and "shadow values" for factors of production [Dantzig, 1949]. Griffin et al. (2005a) used the LP framework to maximize contribution margin with respect to a set of whole-farm constraints on land, labor, and capital under a given weather regime [Boehlje and Eidman, 1984]. Contribution margin is total crop sales revenue minus total direct costs and can be considered returns to resources or fixed costs such as land, labor, and machinery. Shadow values or prices are estimates of the marginal value of a scarce resource and represent the change in contribution margin by using the last unit of resource. The base for comparison was a representative sized Corn Belt farm with a single-equipment set (e.g., one planter and one harvester) using only VM technology for swathing. The base was modified in a series of LP runs to model the NT scenarios.

Five scenarios were compared: (1) a baseline foam, disk, or other VM (10% overlap), (2) addition of LB with basic GNSS availability (±3 dm accuracy), (3) addition of LB with satellite subscription (±1 dm), (4) addition of AG with satellite subscription (±1 dm), and (5) addition of AG with a base station RTK GPS (±1 cm). It was assumed VM NT costs were incurred in all scenarios plus any GNSS NT costs (e.g., disk markers) were installed on the planter.

B.1.1 The Mathematical Linear Programming Model

The optimization problem was specified as a linear programming model in the standard summation notation and written as in Boehlje and Eidman (1984, p. 404–405) as:

$$Max\ \Pi = \sum_{j=1}^{n} c_j X_j \tag{1}$$

subject to:

$$\sum_{j=1}^{n} a_{ij} X_j \le b_i \quad \text{for } i = 1 \ldots m \tag{2}$$

$$X_j \ge 0 \quad \text{for } j = 1 \ldots n \tag{3}$$

where:

X_j = the level of the j^{th} production process or activity

c_j = the per unit return to the unpaid resources (b_i's) for the j^{th} activity

a_{ij} = the amount of the i^{th} resource required per unit of the j^{th} activity

b_i = the amount of the i^{th} resource available

Each GNSS NT scenario changed information relative to the extent the technology was used. The LP objective value results indicate (1) the timeliness benefit of adding GNSS NT and (2) the benefit of increasing farm size without changing equipment sets while remaining timely. Shadow values were examined to determine if planting or harvesting became untimely by considering the number of time periods with a non-zero shadow value. Time periods are generally one week during peak field operations.

B.1.2 Hypothetical Model Farm Scenario

The 1,214 ha baseline farm has three tractors, but only two with GNSS-enabled NT. Field operations were based on conventional tillage production systems. Field operations benefiting from GNSS NT include a 7.3 m chisel plow, 12.8 m field cultivator, 9.8 m tandem disk, 9.1 m grain drill, and 18.3 m planter (Table B.1); the chisel, cultivator, and disk overlap were reduced with each incremental improvement of GNSS guidance accuracy. Although planter overlap and speed were not impacted by NT, GNSS-enabled planting operations were included to model farmer behavior based on their desire for straight and parallel rows; however, GNSS NT allowed planters to be used for additional hours per day and without being outfitted with physical row markers. A chisel is a primary tillage implement that minimizes soil inversion while preserving crop residue. A field cultivator is a secondary tillage implement that incorporates crop residue. A disk is a primary tillage implement that incorporates crop residue while stirring the soil. With VM NT, tractors and implements could be used 12 hours per day and increased to 13 and 15 hours per day for LB and AG, respectively. The farm has two each of the chisel, disk, and field cultivator, one 24-row planter, and one combine harvester with a 12-row corn head on 0.76 m row spacing and 9.1 m soybean head. The conventional tillage practice was to disk, chisel plow, and field cultivate prior to planting corn, and disk and field cultivate prior to planting soybean. Equipment working rate was defined as hectare per hour taking into account speed, size, and field efficiency (Table B.1 and Table B.2). The planter working rate was a constant 12.9 ha hr^{-1} regardless of GPS NT.

Table B.1. Implement Size, Field Efficiency, and Working Rates without GPS Navigation Technology

Implement	Width (m)	Field Efficiency (%)	Working Rate (ha hr^{-1})
Disc	9.8	80	6.6
Chisel Plow	7.3	85	5.3
Field Cultivator	12.8	85	11.4
Boom Sprayer	36.6	55	36.4
Drill (Soybean)	9.1	70	6.4
Planter (corn)	18.3	70	12.9
Harvester (corn)	9.1	85	4.8
Harvester (soybean)	9.1	85	4.8

For LP models, not only were the absolute price values important, but also the price ratios. LP models are typically used for long-term planning horizons and not for short-term management during a single year; therefore, prices and yields representative across several years were chosen. Corn and soybean prices were \$0.197 kg^{-1} and \$0.456 kg^{-1}, respectively, for a price ratio of 2.48. Corn and soybean base yields were expected to be 11.80 Mg ha^{-1} and 3.97 Mg ha^{-1}, respectively, when planted and harvested in the optimal time periods. Per-hectare variable costs were \$963.71 and \$481.86 for corn and soybean, respectively. Yield and variable cost ratios were 0.31 and 0.50 for corn and soybean, respectively.

B.2. Analysis

Benefits of GNSS NT systems were evaluated by incrementally changing the model to reflect effects that each NT had on working rates, workday, equipment availability, and area farmed in a timely manner. Changes to the model were cumulative. Each change was added to the model using parameters from the previous step. This was done by initially changing the working rate, then increasing the number of hours per day that unpaid labor worked, then increasing equipment use hours. Unpaid labor is family labor compensated from net farm income. With VM NT, 10% overlap is assumed, the level of advertised GPS accuracy was assigned to be the overlap for GNSS NT, and 0.05 m overlap for RTK-AG (Table B.2), affecting working rate calculations.

Table B.2. Working Rates (WR) and Overlaps for Field Operations Benefiting from GPS NT

	9.8 m Tandem Disk		7.3 m Chisel Plow		12.8 m Field Cultivation	
GNSS NT	WR (ha hr^{-1})	Overlap (m)	WR (ha hr^{-1})	Overlap (m)	WR (ha hr^{-1})	Overlap (m)
VM NT	6.86	0.98	5.23	0.73	11.33	1.28
3 dm LB	7.41	0.3	5.57	0.3	12.29	0.3
1 dm LB	7.55	0.1	5.71	0.1	12.50	0.1
1 dm AG	7.55	0.1	5.71	0.1	12.50	0.1
1 cm AG	7.60	0.05	5.76	0.05	12.53	0.05

Finally, farm size was increased to bring planter capacity utilization during the last time period to a level similar to the base, conditional upon other operations not being adversely affected (i.e., harvester capacity as measured by the number and magnitude of shadow values) (Table B.3). Timeliness was measured by the hours of planting for each time period. A farm remains timely if planting is completed by a base number of hours per period.

B.2.1 Mathematical Model Results

Initial LP runs were made with no GNSS NT. In the base, a contribution margin of $1,452,173 was realized (Table B.3). Adding a LB with 3 dm accuracy increased the contribution margin by $34,530 (Table B.3) or $28.44 ha^{-1} just from increasing working rates of the chisel and field cultivator. When the hours per day that equipment was used increased from 12 to 13 hours per day, the contribution margin increased by $49,478 over the base farm or $40.76 ha^{-1} (Table B.4). The next-higher-level NT, a satellite subscription GNSS signal used with the LB or AG to give 1 dm accuracy, yielded an increase of $36,773 (Table B.3) or $30.29 ha^{-1} (Table B.4) above base when only working rates were changed. When the workday was expanded to 13 and 15 hours per day for 1 dm LB and AG, contribution margin increased by $51,513 or $42.43 ha^{-1}. RTK-AG, the highest level of technology tested, increased the contribution margin by $37,364 or $30.78 ha^{-1} for the farm just from increasing timeliness (i.e., reducing yield penalties by increasing working rate). Increasing the number of hours that implements are used increased the contribution margin an additional $57,802 (Table B.3) or $47.61 ha^{-1} (Table B.4).

Table B.3. Change in Returns, Shadow Values, and Planter Capacity Utilization

GNSS NT	Increased Working Rate	Increased Equipment Hours	Increased Farm Size
Contribution Margin (US$ Farm^{-1}) (Base = $1,452,173) [after land costs]			
3 dm LB	34,530	49,478	196,619 [128,619]
1 dm LB	36,773	51,513	219,799 [143,299]
1 dm AG	36,773	57,802	387,360 [251,360]
RTK AG	37,364	57,802	389,062 [253,062]
Shadow Value on Land (US$ ha^{-1}) (Base = $438)			
3 dm LB	541	543	37
1 dm LB	542	545	-10
1 dm AG	542	668	336
RTK AG	543	668	337

The shadow value on land changed as GNSS NT benefits were added. The shadow value is the amount the farmer would be willing to pay for one additional unit of resource (in this case, one hectare of land). Without GNSS NT, the shadow value on land was $438 ha^{-1} (Table B.3). As NT was added, the shadow value on land increased. When the working rate increased, the shadow value increased to approximately $980 for all GNSS NT, or a difference of $541 to $543 (Table B.3). The shadow values in both LB scenarios were unchanged while AG NT increased to $1,106 ha^{-1} when time constraints were relaxed. When additional acres were added to make the farm as timely as the base, all land shadow values reverted to levels similar to the base. This decrease in land shadow value results from a constant harvester capacity with increased equipment set utilization, reducing the value of the next unit of land. The additional value due to GNSS NT could make the difference between a successful land rental bid and being left behind in the competitive Corn Belt market for farmland.

B.2.2 Economic Partial Budget Analyses

A partial budget was created from LP results. Annualized costs were calculated using a 10-year useful life, 8% discount rate, and no salvage value for GNSS NT. For example, the annualized costs of RTK-AG were \$5.19 ha^{-1}, assuming a \$35,000 initial investment (Table B.4). Annual subscription fees for 1 dm correction was assumed to be \$1,500, while the 3 dm accuracy had no annual fee. It was assumed that conventional VM NT were still present and, therefore, the fixed costs of VM were not deducted from the costs of GNSS NT. Annualized GNSS NT costs per hectare were subtracted from returns to the respective GNSS NT (Table B.4). When farm size was not expanded, the 1 dm AG NT was most profitable, followed by RTK AG, 1 dm LB, 3 dm LB, and VM. All GNSS NT were more profitable than VM in all cases. When full benefits of GNSS NT were made by expanding farm size, RTK AG became the most profitable GNSS NT. Economic ranking differs from earlier studies (Griffin et al., 2005a) due to differences in crop prices and GNSS NT cost ratios.

Table B.4. GNSS Navigation Technology (NT) Costs and Returns Relative to Visual Markers as of 2004

	3 dm LB	1 dm LB	1 dm AG	RTK AG
Potential farm size expansion by adding GPS NT (Base farm size 1,214 ha)				
Change in farm size (ha)	162	182	324	324
Navigation Technology Costs (US\$)				
Initial investment US\$	3,000	5,000	18,000	35,000
Annualized cost $farm^{-1}$	540	900	3,240	6,300
Annual subscription fee	0	1,500	1,500	0
Total annual cost $farm^{-1}$	540	2,400	4,740	6,300*
Total annual cost ha^{-1}	0.44	1.98	3.90	5.19
Total annual cost ha^{-1} with added ha	0.39	1.72	3.08	4.10
Returns to fixed costs above base (US\$ ha^{-1})				
Returns (no added land)	40.76	42.43	47.61	47.61
Returns (added land)	93.47	102.65	163.43	164.54
Returns to fixed costs minus GNSS NT above base (US\$ ha^{-1})				
Returns (no added land)	40.31	40.46	43.71	42.42
Returns (added land)	93.08	100.93	160.35	160.44

B.2.3 Regional Cost of GPS Outage

Regional costs of GNSS outage can be estimated by a simple summation of the farm-level losses for all affected farms and can be as complex as including other direct and indirect economic impacts using community analysis methodology. Assumptions concerning the number of farmers making use of GNSS and the value of production for the average farm must be made. The USDA Census of Agriculture for 2002 stated that there were 26,900 farms in Illinois, Indiana, Iowa, and Ohio, all in the North Central Region of the U.S., that have more than \$500 in annual sales. According to estimates from Schimmelpfennig and Lowenberg-DeBoer (2020), 70% of farms use AG. Using the farm-level value of GNSS-enabled NTs presented in Table B.4, the regional economic loss due to a GNSS outage is presented in Table B.5. Summing the farm-level losses of a GNSS outage across the North Central region of the U.S. for the entire crop cycle (i.e., planting to harvest) could have reduced farm gate values by more than a half billion dollars almost 20 years ago. Today, if adjusted for inflation and growth of technology adoption, it could be well over a billion. Note that while the proposed scenario is an extreme case, the impact of a GNSS outage lasting a few days during a critical part of the crop cycle (e.g., planting) could be hundreds of millions of dollars or more.

Table B.5. Regional Farm-Level Costs of a GNSS Outage at 2004 Levels

GNSS-NT	Farm Value of GNSS-NT	Farms with GNSS-NT (%)	Farms Affected	Regional Loss (USD)
1 dm AG	57,802	70	18,830	$1,088,411,660
RTK AG	57,802	70	18,830	$1,088,411,660

The estimates presented reflect the summation of benefits not realized due to lack of GNSS; however, this is not a complete analysis, especially for current conditions. Rather than improving efficiency, AG has become required technology in the absence of visual row markers that are not always available on planters and sprayers. Larger-width equipment are where guidance is the most useful and are also most likely to not have visual marker systems.

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