Cost Of Reliance On GNSS For Autonomous Cotton Harvest: Assessing Potential Vulnerability Of Autonomous Navigation Systems To A GNSS Outage

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Summary

Agricultural production has become more reliant on global navigation satellite systems (GNSS) and subsequently more vulnerable to outages. Recent GNSS outages associated with solar storms delayed planting operations across portions of the Great Plains, Southeast, and Corn Belt, especially for newer larger machinery without physical row markers. Assessment of hypothetical GNSS outages during harvest indicated that small autonomous systems were penalized up to $14,000 per week for a representative sized 2000-acre cotton farm; but severity of penalty was sensitive to timing and duration of outage.

Sources of GNSS outage

Selective availability was disabled for the civilian Global Positioning System (GPS) signals in 2000, however outages and degradation of global navigation satellite systems (GNSS) may result from a variety of natural and artificial sources. Regardless of the source of the unplanned outage or degradation, farm-level yield and profitability penalties can be modeled with familiar downtime methods.

Natural events may include ionospheric scintillation which causes the radio waves to be modified and can prevent a position from being calculated at its extreme or, in less severe scenarios, reduce accuracy (SWPC NOAA, 2024). Solar events on May 10, 2024, produced a geomagnetic storm resulting in an outage in several states across the American Heartland lasting for more than 4 hours. Solar originated geomagnetic storms, e.g. space weather, have occurred on 11-year cycles since 1750 (Bishop et al., 2022). During solar cycle maximums, the probability of solar storms and disturbances increase. Solar storms sufficient to cause radio blackouts occur about two thousand times each cycle (Bishop et al., 2022). Only the most recent cycles have contemporaneously occurred with artificial satellites such as GNSS. Radio blackouts or reduced accuracy are a grave concern for any vehicle using these signals as a full or partial source of navigation. Consequently, the aviation industry has been tracking both space weather (FAA, 2016) and artificial events such as GNSS jamming and spoofing systems (FAA, 2024; Langley, 2024) to evaluate the consequences of these events.

Reliance of autonomous robots on GNSS

Given automated robotic harvest is reliant solely or in part upon GNSS for guidance, abrupt unplanned outages have substantial and immediate adverse impacts with little to no warning. While current single-pass harvesters may continue to operate during GNSS outage without automated guidance and georeferencing sensor data (i.e., yield monitor data), autonomous robotic harvesters are more vulnerable and may become completely inoperable during GNSS outage. Given that status quo harvest systems were unaffected during a GNSS outage, agronomic and economic losses were estimated for automated robotic systems.

GNSS outages have lasted from a few minutes to several hours and sometimes with lingering aftereffects; therefore, sensitivity of losing between 1 hour and the total number of hours available for fieldwork during a given week were considered. To model this reliance during an outage, the probabilities of fieldwork days are assumed to go to zero for autonomous robots for some length of time in hours or days, e.g., duration, during one specific week.

Modeling harvest systems

The example results presented here were based on the following assumptions for Midsouth cotton production timing and yield potential.

- lint price is $0.94 per pound
- maximum harvestable yield is 1555 pounds per acre, 1452 for single pass
- variable cost of harvest for robots are $0.04 per pound
- weekly carryover penalty is 1%
- total cotton acreage of 2000 acres across multiple fields

Single-pass systems are current status quo harvesters and were able to harvest a potential maximum yield of 1452 pounds per acre during the best time periods. Small autonomous systems were able to harvest 1555 pounds per acre if seed cotton were harvested within one week of bolls opening; but with a 1% weekly carryover penalty if transferred to the next week.

Impact of GNSS outage

When considering single pass systems, production and revenue calculations were unchanged. Harvest continues as normal but without assistive automated guidance and logging georeferenced sensor data. The lack of farm data may have limited immediate impact on farm profitability but may have longer auxiliary penalties to the farm operation, seed sales, service providers, and agricultural retail locations especially when on-farm experiments were conducted.

When considering autonomous robotic harvesters, GNSS outages were more severe than single pass systems. Under the baseline assumptions without a hypothetical GNSS outage, the autonomous and status quo systems were associated with returns to fixed costs of $1,390,749 and $1,297,856, respectively, for a $92,893 advantage to small autonomous robots. Calculations for autonomous systems without an outage can be considered as baseline results to compare returns associated with an outage.

Out of 3,110,000 pounds of harvestable seed cotton on 2000 acres, 217,059 pounds were unharvested using single-pass systems due to exhausting available hours to harvest during the best time periods and harvesting remaining acreage during weeks with less than 100% potential harvestable yield. Single-pass systems harvested 2,892,941 pounds across the 2000-acre farm; resulting in $1,297,856 returns to fixed costs for any duration or timing of GNSS outage.

For autonomous systems, up to 1,048,078 pounds were unharvested depending on severity of GNSS outage, especially the specific week of occurrence and duration of the outage. Returns were reduced as duration of outage increased up to all hours suitable for fieldwork had been offset; in this case 52 hours per week (Figure 1). Only weeks associated with the opportunity to harvest seed cotton from opened bolls were considered. The maximum loss for autonomous systems was calculated when an outage occurs during the week ending September 1. Returns to fixed costs of $1,377,051 were calculated indicating a penalty of $13,699 per farm (Figure 1). Less than 10 hours duration of outage during this week were not associated with any penalties; however, the following week, e.g., week ending September 8, was associated with a loss of $203.06 even for a 2-hour outage.

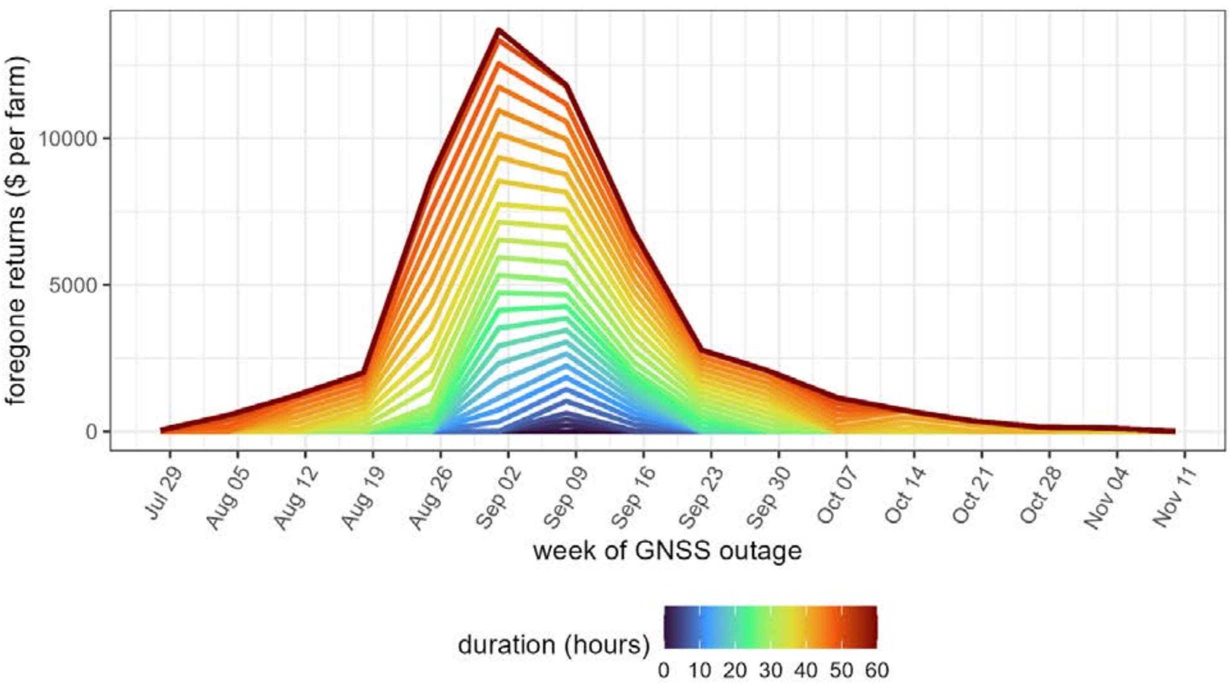

Figure 1. Change in returns for autonomous harvest systems due to GNSS outage

Discussion and Future Work

The optimal decision for farm operators during extreme GNSS outages (due to space weather or jamming) is to remain patient (i.e., not panic) and wait until positioning systems return to operational levels. Understanding how yield, quality, and economic losses are impacted from delayed harvest is important when considering risk mitigation. Space weather is recognized as a threat to modern agricultural technology; however, GNSS outages may arise from other natural or artificial events.

The first generation of autonomous robotic harvesters are expected to be reliant upon GNSS for navigation, however the second generation of technology will likely use alternative guidance such as machine vision and possibly a dedicated terrestrial-based telemetry system mated with artificial intelligence. Considering the within-farm losses if autonomous systems become inoperative during harvest, longer-term development of autonomous cotton harvest systems includes designing in a non-GNSS mode using machine vision, telemetry, or manual orientation.

Results presented here have broader implications than small autonomous robotics that are being developed across the Cotton Belt. Large field-scale driverless agricultural equipment are being implemented to perform similar tasks that human operators have traditionally conducted. GNSS outages would deem those automated equipment inoperative.

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