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Towards Precision Management: Part I Global Navigation Satellite Systems (GNSS)

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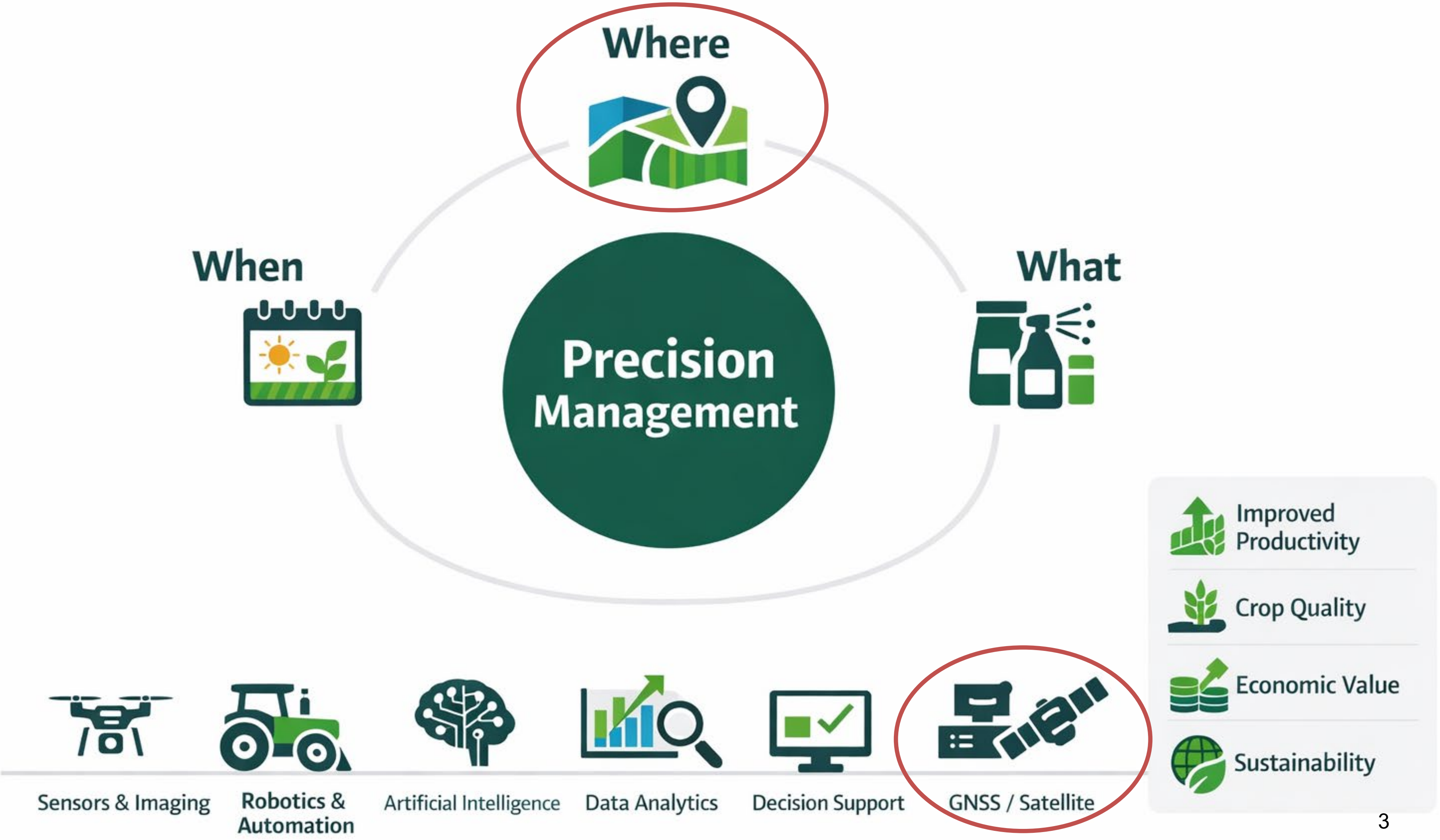
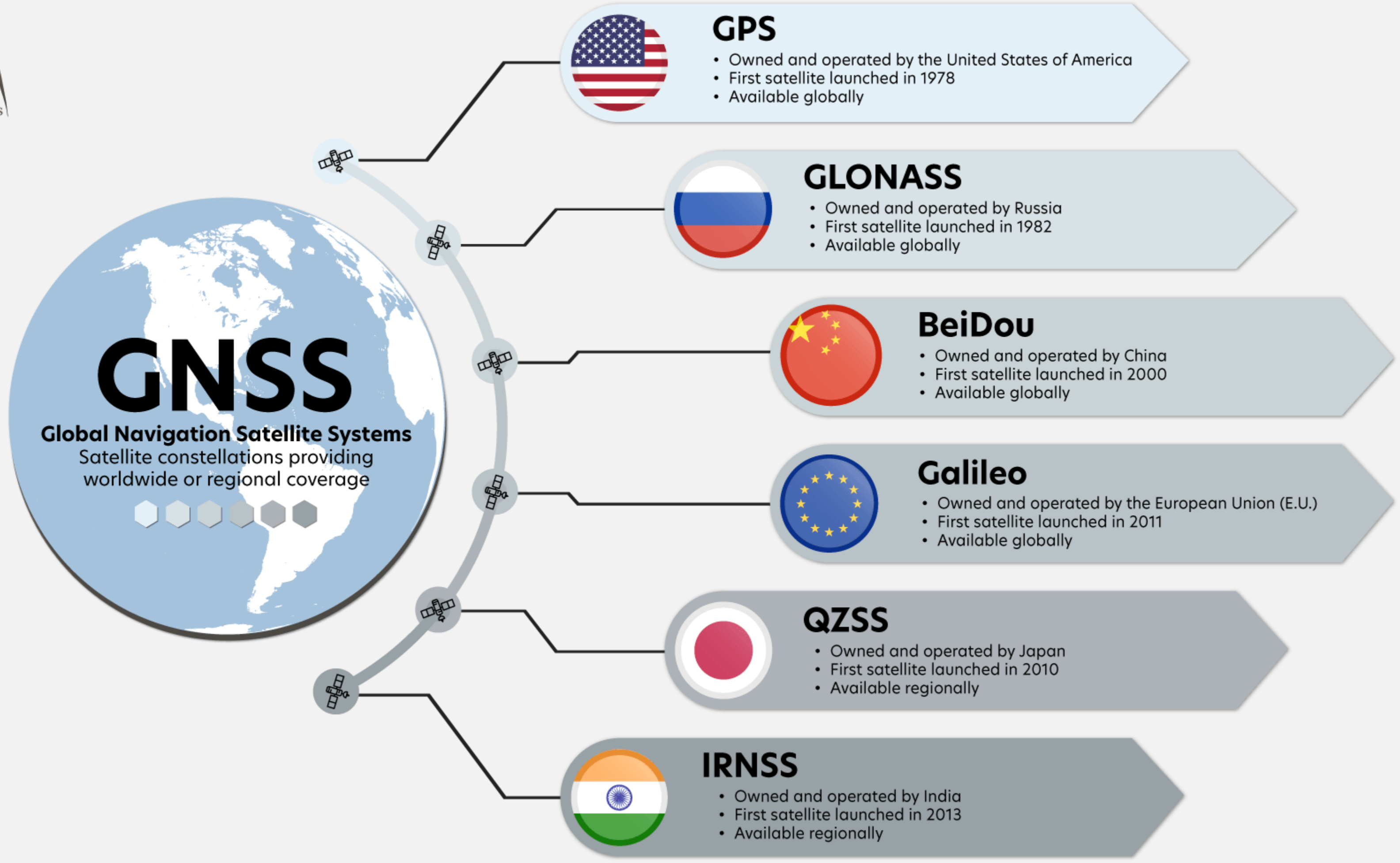
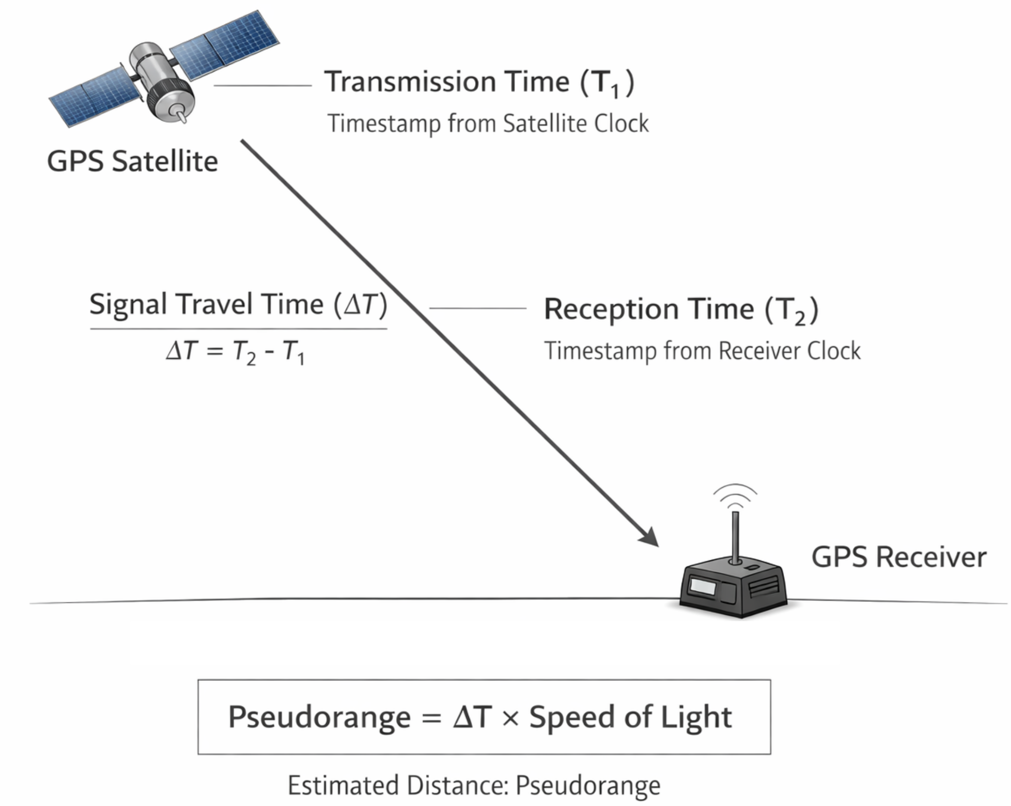

Where
When
Precision Management
What
Improved Productivity
Crop Quality
Economic Value
Sustainability
Sensors & Imaging
Robotics & Automation
Artificial Intelligence
Data Analytics
Decision Support
GNSS / Satellite

EOS
Positioning Systems

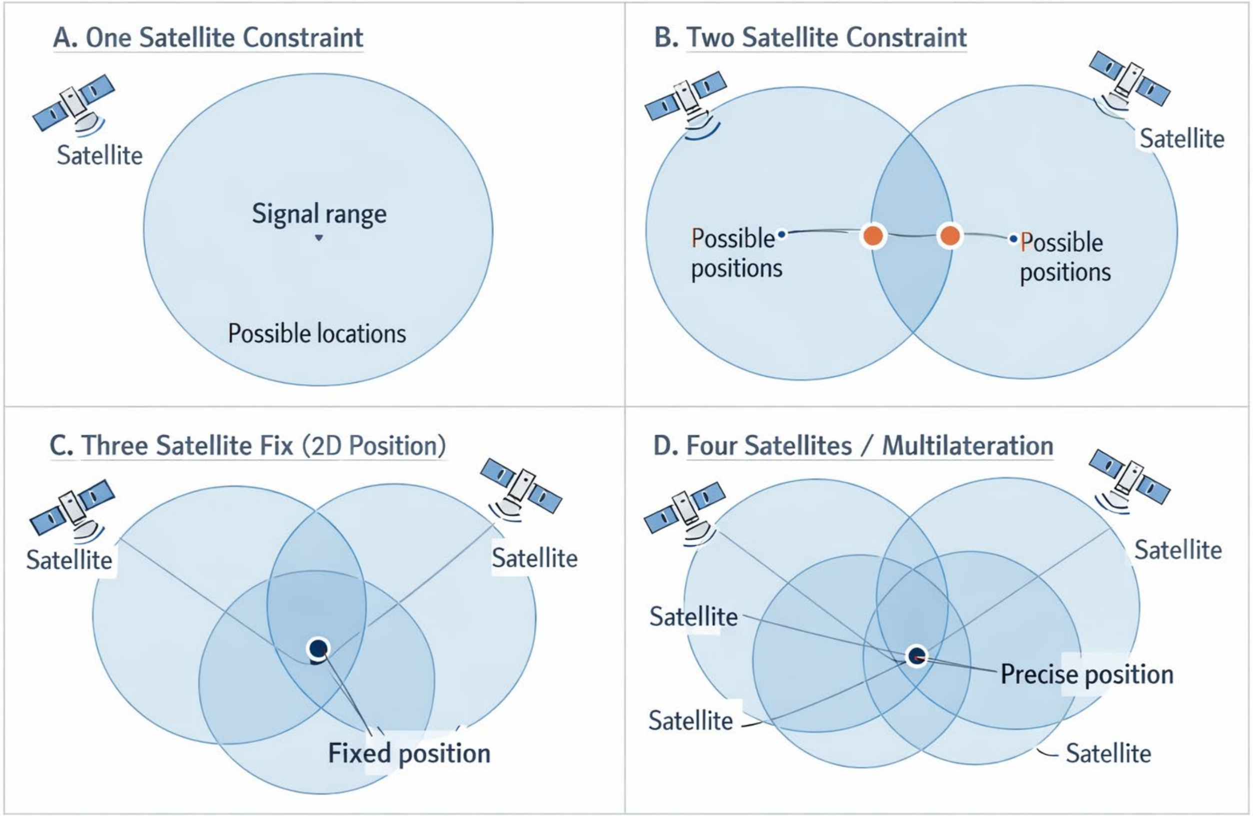


How GPS Estimates the Distance

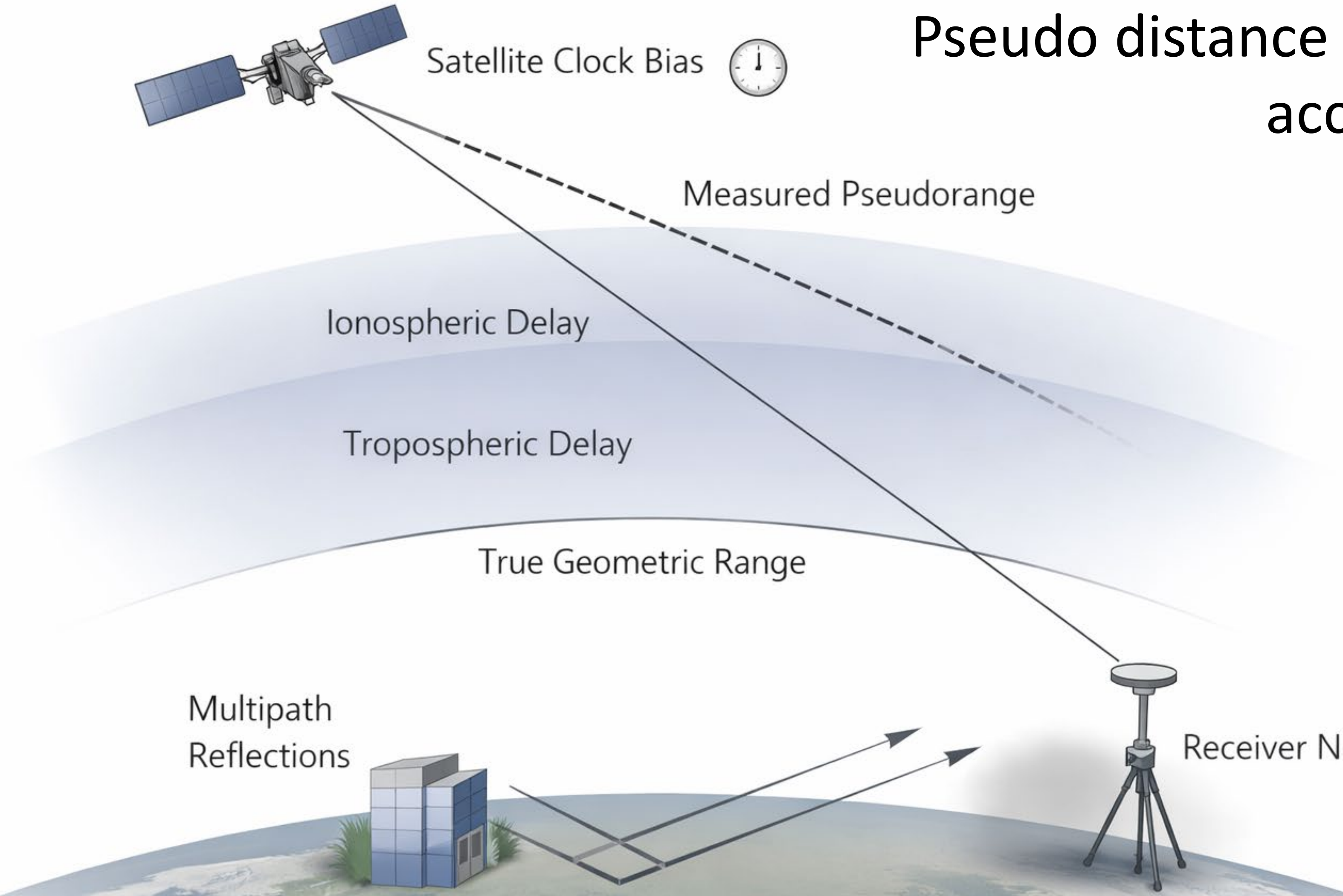


Speed of light is a constant value
299 792 458 m / s

Trilateration and Multilateration



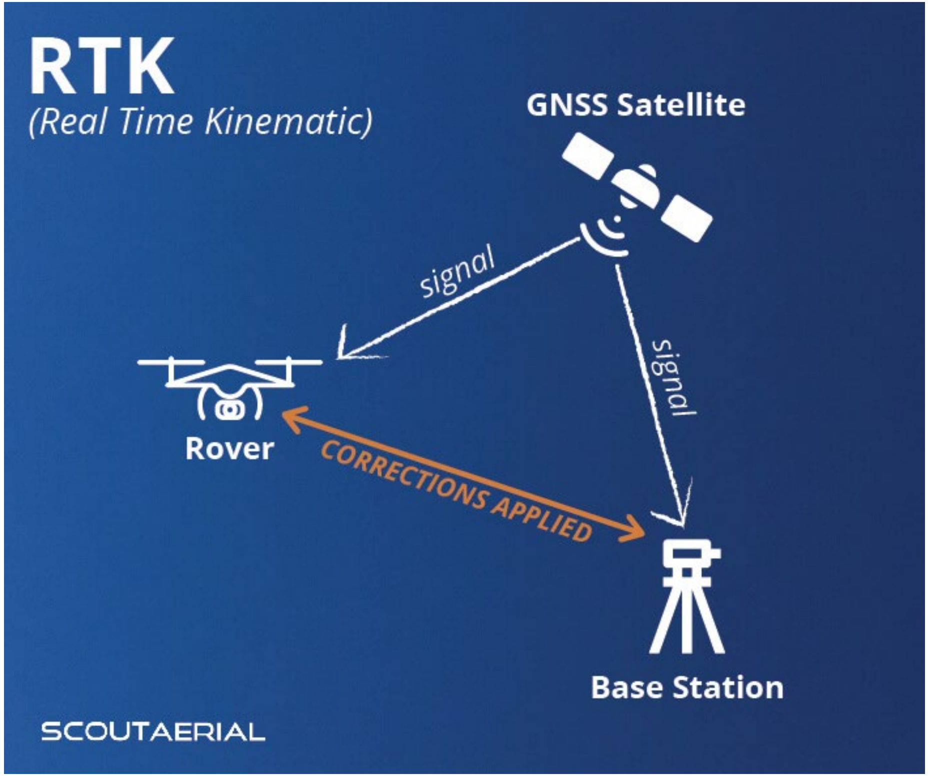
Pseudo distance is not accurate

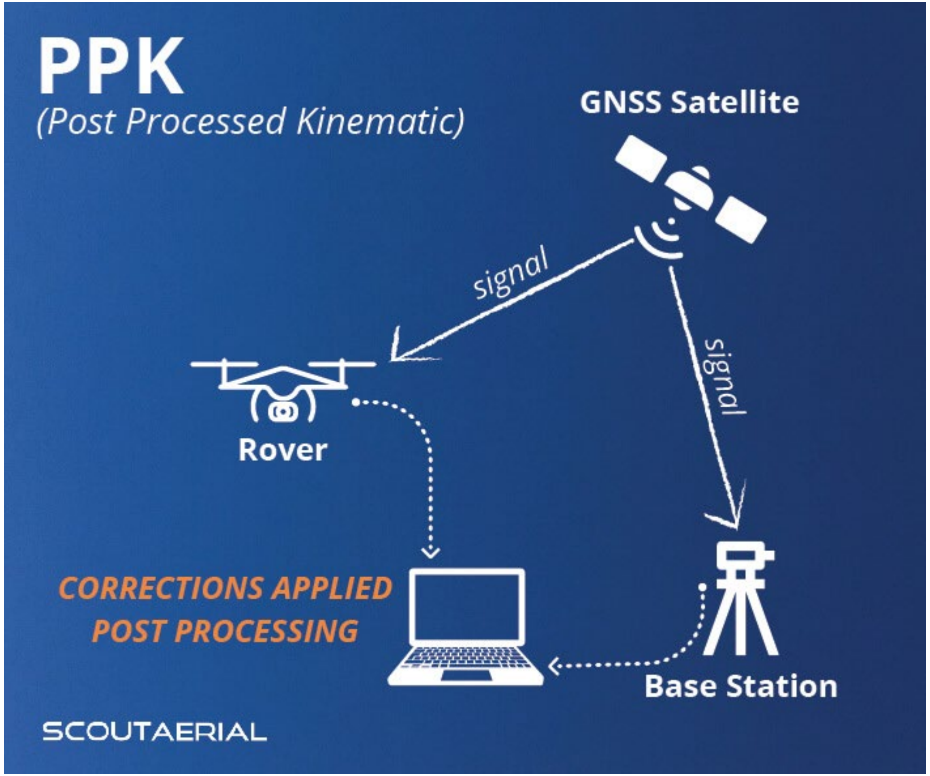


Higher Accuracy

- Civilian GPS can achieve up to several-meter accuracy such as DGPS
- Centimeter or sub-inch accuracy
  - Real Time Kinematic GPS (RTK)
  - Post Processing Kinematic GPS (PPK)

How RTK and PPK Work





Key Components

Criteria	RTK (Real-Time Kinematic)	PPK (Post-Processed Kinematic)
Needed Components	**Base station, GNSS Rover, *Communication***	**Base station, GNSS Rover, *Post-processing Software***
Accuracy	High (cm-level)	High (cm-level)
Real-time Processing	Yes	No
Post-Processing	No	Yes
Base Station Requirement	Yes	No (but reference data needed)
Pros	Real-time high-precision positioning, Useful for immediate applications	More reliable in areas with poor signal, No need for a constant radio link
Cons	Requires continuous connection to base station, Susceptible to signal interference	Delayed results due to post-processing, Requires additional processing time

Technologies in the Box for Precision Orchard Management: Global Navigation Satellite System

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Keywords: GPS, precision management, RTK, PPK

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Precision crop load management requires accurate GPS coordinates for each tree in the orchard. In this article we present options for GPS systems with sufficient accuracy to use with precision crop load management.

Precision management is becoming essential for growers aiming to optimize yield and quality while also reducing costs to maintain competitiveness in the market. This approach integrates various technologies and techniques such as yield monitoring and mapping, precision soil sampling and mapping, and variable rate applications (like sprays and pruning). For apple cultivation, Precision Apple Crop Load Management (PACMAN) has proven particularly effective in boosting both apple quality and profitability. Notably, the integration of new digital technologies, including imaging-based bud, blossom and fruit counts, has greatly enhanced the implementation of PACMAN by growers (Robinson et al., 2022, Wallis et al., 2023, and

satellite geometry, and signal obstructions (Kaplan et al., 2017). This level of accuracy is suitable for a wide range of civilian applications, including car navigation, hiking, and other general uses where highly precise positioning is not crucial. SPP utilizes signals that are freely available from GPS satellites without any encryption, making it accessible to anyone with a GPS receiver.

Cross-brand Repeatability

- What if multiple GNSS receivers are used in my orchard?
  – Base station location differences
    - Proper location survey and GPS installation
  – Compatibility of communication
    - Correction message formats: CMR/CMR+, RTCMv2/RTCMv3
    - Output formats for other software
  – Communication for all GNSS
    - Radio (messaging), Internet (NTRIP), or satellite-based (RTX)

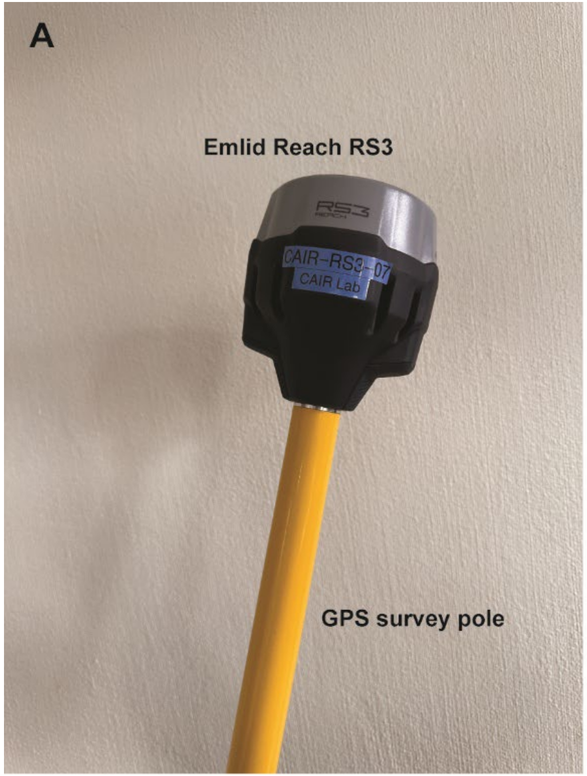
RTK-GPS Products

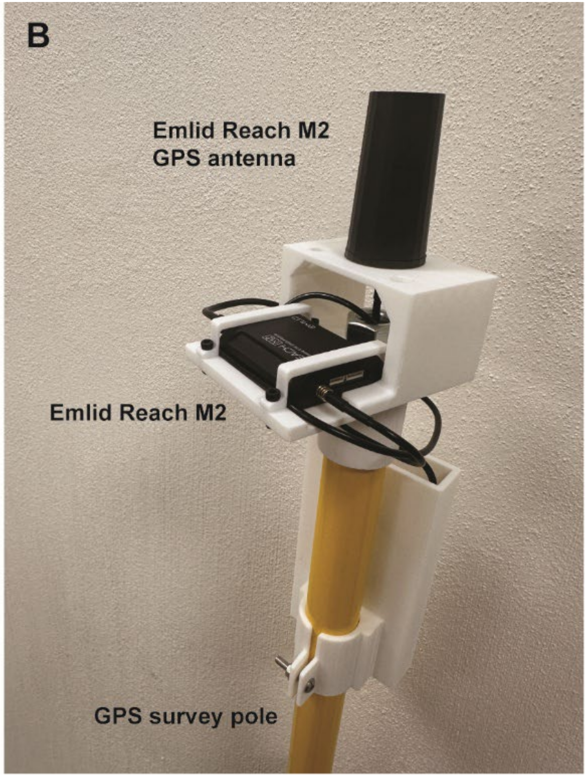
Device Name	GNSS module	GPS antenna integrated	Price	Base station/rover
NovAtel Smart7	RTK+IMU	Yes	~$7,000	Both
Trimble AgGPS 542	RTK	No	~$10,000	Base station
Trimble Zephyr 2*	N/A	Antenna itself	~$500	Needs to be paired with AgGPS 542.
Emlid Reach RS2+	RTK only	Yes	$2,599	Both
Emlid Reach RS3	RTK+IMU	Yes	$2,999	Both
Emlid Reach M2	RTK only	Yes	$749	Rover
uBlox ZED-F9P-02B	RTK only	No	$130 (chip itself)	Both Requires a GPS antenna
TOPGNSS TOP106	n/a	Antenna itself	$200	Needs to be paired with a GNSS module

RTK-GPS Configurations

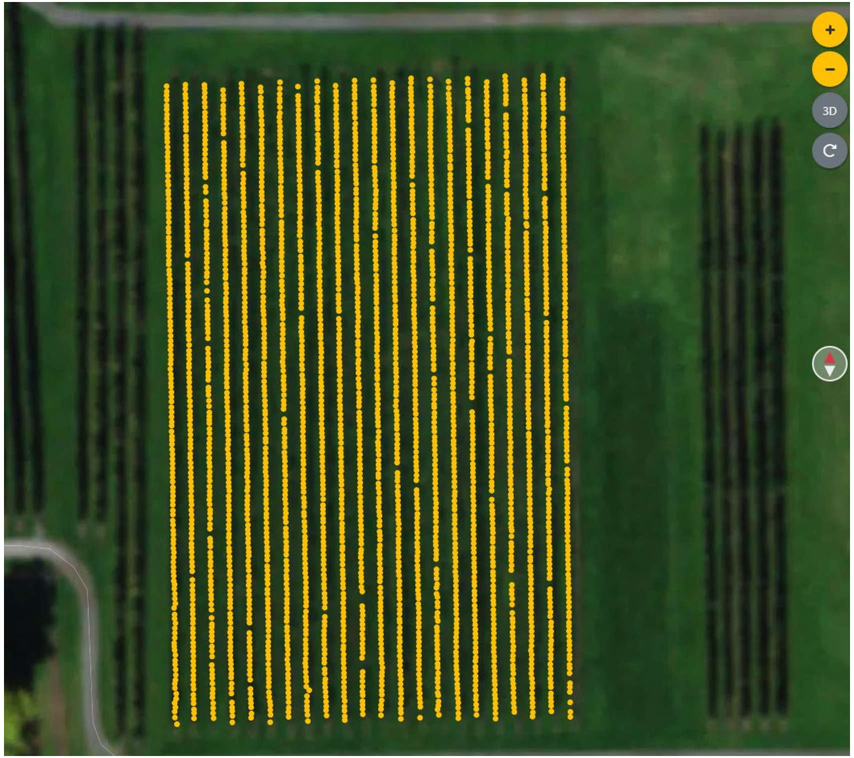
Configuration ID	Base Station GPS	Rover GPS	Communication	Applications
1	Trimble AgGPS 542	Emlid Reach RS3	NTRIP and local radio	Navigation and survey
2		Emlid Reach M2	NTRIP	Survey
3	NovATel Smart7	NovAtel Smart7	Local radio	Navigation
4		Emlid Reach RS3	NTRIP	Survey
5	Emlid Reach RS2+	Emlid Reach RS3	Local NTRIP and local radio	Navigation and survey
6		Emlid Reach M2	Local NTRIP and local radio	Survey
7	Emlid Reach RS3	Emlid Reach RS3	Local NTRIP and local radio	Navigation and survey
8		ublox ZED-F9P-02B with TOPGNSS TOP 106	NTRIP	Navigation

RTK-GPS Rover Example





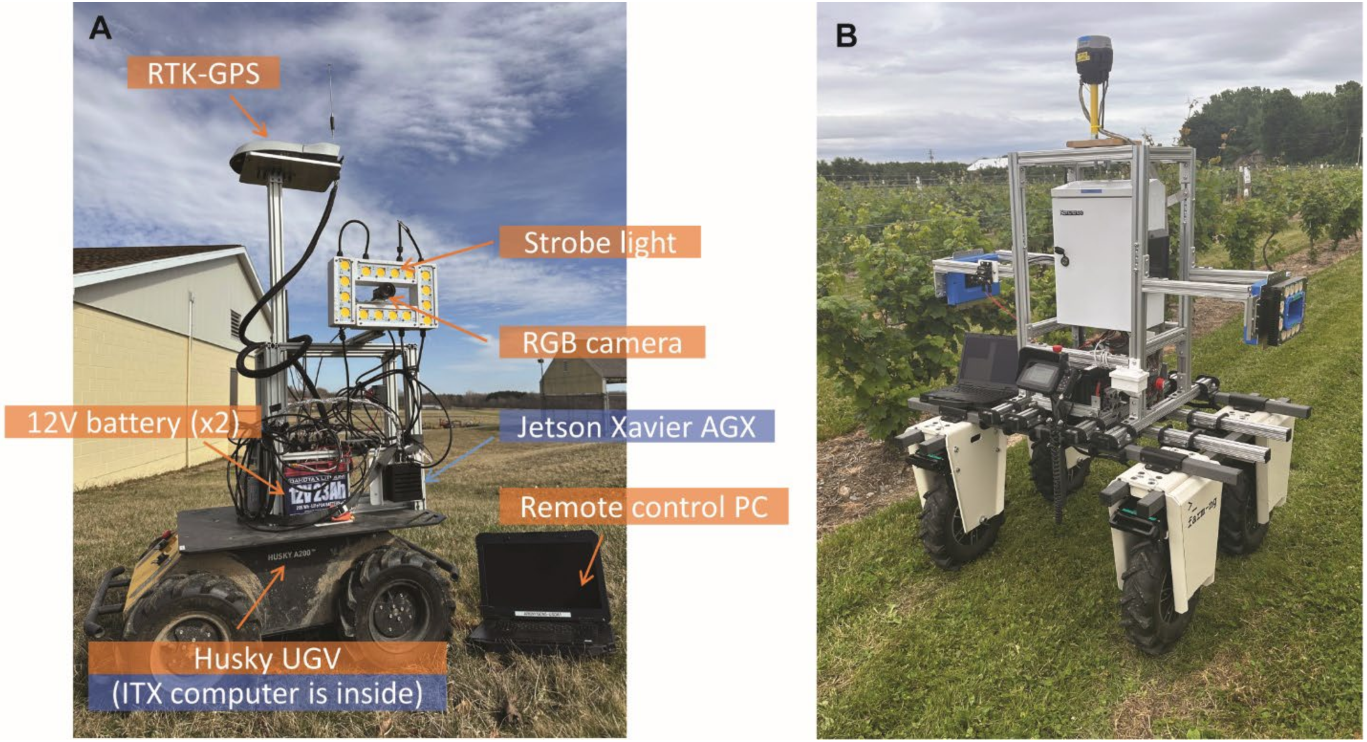
Geo-survey Performance



Configuration 1
Trimble AgGPS 542
Emlid Reach RS3
NTRIP and local radio

Performance
Designed tree spacing: 3 ft (0.91 m)
Measured average: 3.11 ft (0.95 m)
Std: 0.89 ft (0.27 m)
RTK fixed rate: 99.96%

Mobile Robot for Nav Test



Navigation Performance

RTK-GPS Configuration	Positional Deviation	Heading Deviation
Configuration 1	0.05 m ± 0.01 m	1.2° ± 0.9°
Configuration 3	0.08 m ± 0.01 m	1.15° ± 0.96°
Configuration 5	0.07 m ± 0.01 m	1.45° ± 1.1°
Configuration 7	0.08 m ± 0.01 m	1.2° ± 0.8°
Configuration 8	0.05 m ± 0.03 m	1.8° ± 1.1°

Recommendations

- Receivers
  - Most reliable: Trimble (or Raven) and NovAtel (~$10k)
  - Most economic: ublox (~$200) or Reach M2 ($700)
  - Best balanced: Reach RS3
- Communication
  - NTRIP (preferred)
- Format
  - RTCM (Radio Technical Commission for Maritime)

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Affordable RTK GPS Solutions for Precision Management of Perennial Crops

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Keywords: real time kinematics, GPS, precision crop load management, precision viticulture

This research was supported by the NY Apple Research and Development Program.

Real time kinematic (RTK) GPS is the most widely used positioning technology. However, its adoption among specialty crop growers has been limited due to both technological barriers and cost concerns. Our goal was to evaluate recent affordable RTK GPS commercial solutions that represent an important step toward precision management in trellised cropping systems such as modern orchards and vineyards.

Precision management has emerged as a critical approach for improving agricultural productivity, sustainability, and profitability. For example, our recent work on precision crop load management in apples focuses on managing an optimal number of fruit per tree to achieve consistently high-quality produce and stable yields, ultimately benefiting the apple industry (Lawrence et al., 2025; Gonzalez et al., 2023; Robinson et al., 2024). By applying the right treatment at the right location and time, growers can enhance crop performance in terms of yield, quality, and consistency, while optimizing resource use and reducing environmental impacts. Achieving these goals depends on the ability to accurately determine the location of crops, field features, and agricultural machinery.

Real-time kinematic global positioning systems (RTK GPS) play a central role in providing the centimeter-level positional accuracy required for many precision agriculture applications. Unlike standard GPS, which typically provides meter-level accuracy, RTK GPS uses correction signals from a base station or network to greatly reduce positional errors. This level of accuracy enables tasks such as geo-referencing individual plants, guiding autonomous vehicles, mapping field variability, and executing variable rate treatments with minimal overlap or gaps.

The adoption of RTK GPS has been widespread in field crop production, where it supports applications such as automated steering, planting, and input applications. However, in specialty crops such as high-density orchards and vineyards, adoption has been slower due to higher equipment costs, technical barriers, and limited communication infrastructure. Recent advancements in affordable RTK GPS solutions have the potential to bridge this gap, providing growers with cost-effective tools to implement precision management practices. Such systems can support both static applications, such as plant or infrastructure geo-surveys, and dynamic applications, including autonomous navigation of intelligent and robotic equipment. As perennial crop production continues to face labor challenges, increasing operational costs, and the need for sustainable resource use, the role of RTK GPS in enabling automation and precision management will become increasingly important.

We have recently provided an overview of the fundamentals of GPS and RTK GPS technologies (Jiang et al., 2024). However, many growers remain uncertain about whether it is worthwhile investing in high-end RTK GPS systems and whether emerging affordable RTK GPS solutions can deliver reliable performance. To address these questions, we evaluated several representative affordable RTK GPS systems in both orchard and vineyard settings, providing a quantitative assessment of their performance. The results of this study aim to support growers in making informed decisions about investing in RTK GPS technology.

RTK-GPS devices and various configurations

As explained in the previous article (Jiang et al., 2024), an RTK GPS system consists of three components: a base station GPS receiver, a rover GPS receiver, and communication infrastructure. Major agricultural equipment companies offer RTK GPS modules as part of their integrated solutions, such as those from AgLeader and CNH Industrial, or sell dedicated RTK GPS products, such as those from Trimble and Raven. In recent years, many affordable RTK GPS products have become commercially available, allowing the farming community to adopt this technology in a cost-effective way. These emerging solutions also rely on open source RTK correction standards, such as radio technical commission for maritime services (RTCM) v2 and v3, without additional fees, which enables smooth integration with other advanced agricultural equipment including intelligent and robotic sprayers. However, it remains uncertain whether these affordable RTK GPS solutions can consistently deliver reliable positioning performance and achieve the claimed accuracy, which makes them worthy of testing. In this study, we selected products from both established suppliers, such as Trimble and NovAtel, and more affordable options for growers (Table 1).

After acquiring the base station and rover GPS receivers, an RTK GPS system can be configured with different communication methods, such as the network transport of RTCM via Internet protocol (NTRIP) or a local radio network. Recent developments also allow a local WiFi network to broadcast RTCM correction signals without using the Internet, creating a local NTRIP solution. In this study, we included these communication options and evaluated their performance in perennial cropping systems such as orchards and vineyards (Table 2). Based on their intended uses, we categorized the test cases as either for plant location geo-survey or for robot navigation. These two categories represent static and dynamic application scenarios, both of which are critical for precision management. For example, crop plants such as apple trees or grapevines need to be geo-referenced to determine their exact location. The RTK GPS system can then be used to obtain crop performance, such as crop load, and subsequently guide agricultural equipment, such as sprayers, to apply variable

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Thanks for your attention!

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