The Future of Satellite-Based Positioning and Timing

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The Future

- **“Most of our future lies ahead,” Denny Crum**
- **“The only thing we know about the future is that it is going to be different,” Peter Drucker**
- **“Prediction is very difficult, especially about the future,” Niels Bohr**
- **“The problem with the future is that it keeps turning into the present,” Bill Watterson**

Some Previous Predictions

- "Radio has no future."
  "X-rays are clearly a hoax."
  "The aeroplane is scientifically impossible."
  Royal Society president William Thomson, Lord Kelvin, 1897-1899
- "There is not the slightest indication that nuclear energy will ever be obtainable. It would mean that the atom would have to be shattered at will."
  Albert Einstein, 1932
- “Where a calculator like the ENIAC today is equipped with 18,000 vacuum tubes and weighs 30 tons, computers in the future may have only 1,000 vacuum tubes and perhaps weigh only 1½ tons.”
  Popular Mechanics, 1949
- "I think there's a world market for about five computers.“
  Thomas J. Watson, chairman of the board of IBM, 1958

Some Previous Predictions about GNSS

- First GPS Block IIF satellite launch in 2005, 1997
- GLONASS full constellation of 24 operating SVs in 2009, 2006
- Fully operational 30 SV Galileo constellation in 2008, 2002

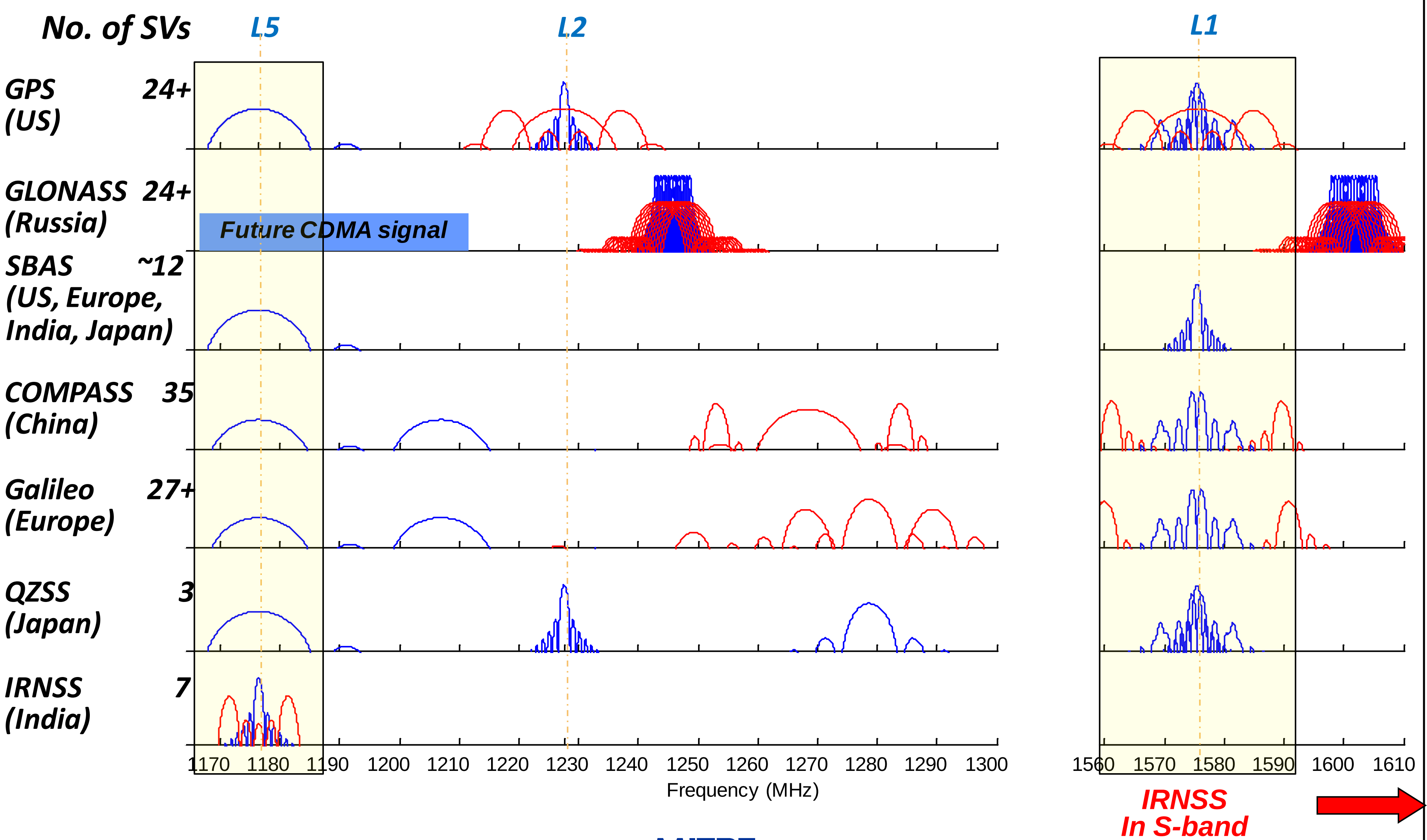
Last Century's Civil Signal Designs for Satellite-Based Navigation and Timing

Technical Characteristic	*Consequence*
Transmitted on single center frequency	Residual ionospheric errors, no frequency diversity to avoid interference
Data biphase modulated onto all spreading symbols	Less robust signal tracking
Short, repeating spreading codes	Higher multiple access interference; false lock
Lower transmit power	Limited performance indoors and in interference
Weak error correction and error detection in data message design	Poorer performance indoors and in interference; longer time to first fix
Narrow bandwidth BPSK-R spreading modulations	Poorer tracking accuracy, greater sensitivity to multipath and interference, greater multiple access interference

Civil Signal Designs for Modernized and New Systems

- Two and three center frequencies
- Pilot components not modulated by data
- Longer spreading codes; overlay codes on pilot components
- Higher transmit power
- Strong error correction; very strong error detection
- Wider bandwidth spreading modulations using BOC
- Highly interoperable signals to be transmitted by multiple systems—up to 100 satellites

Future Signals



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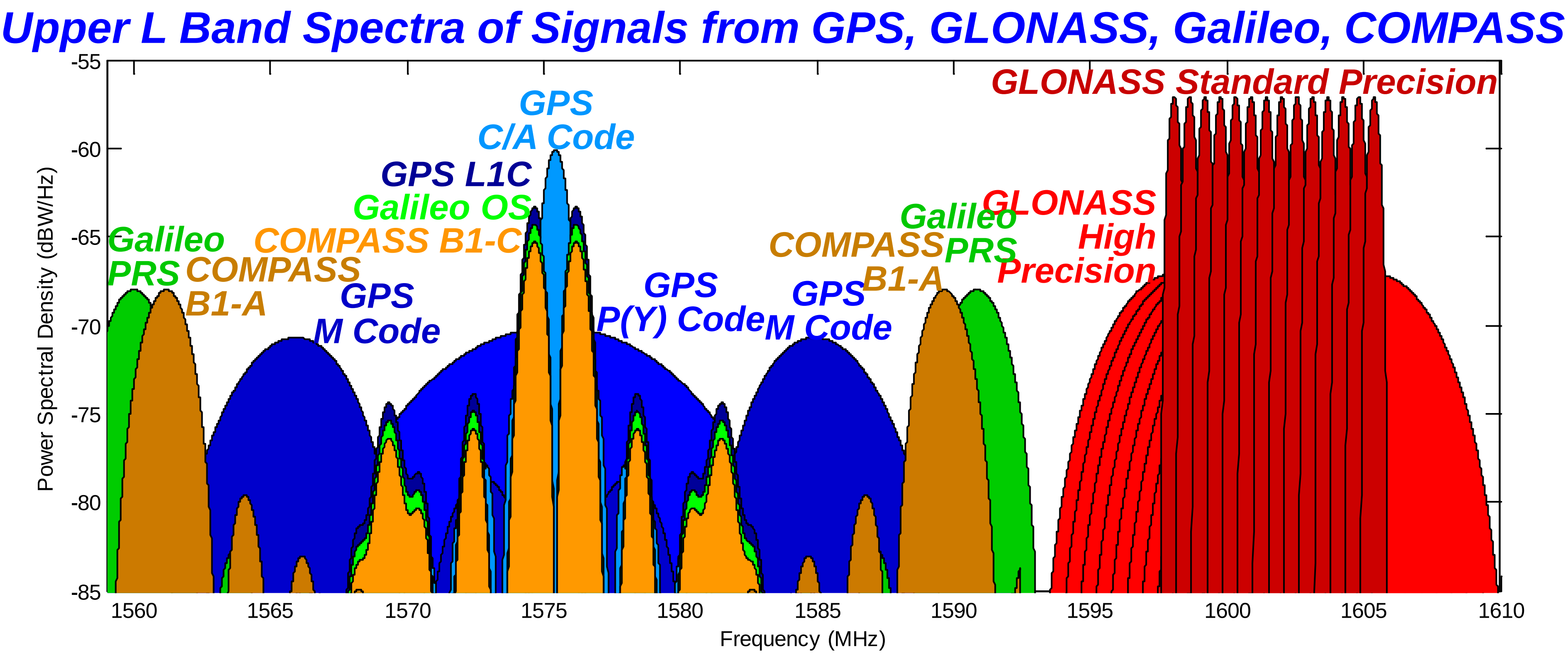
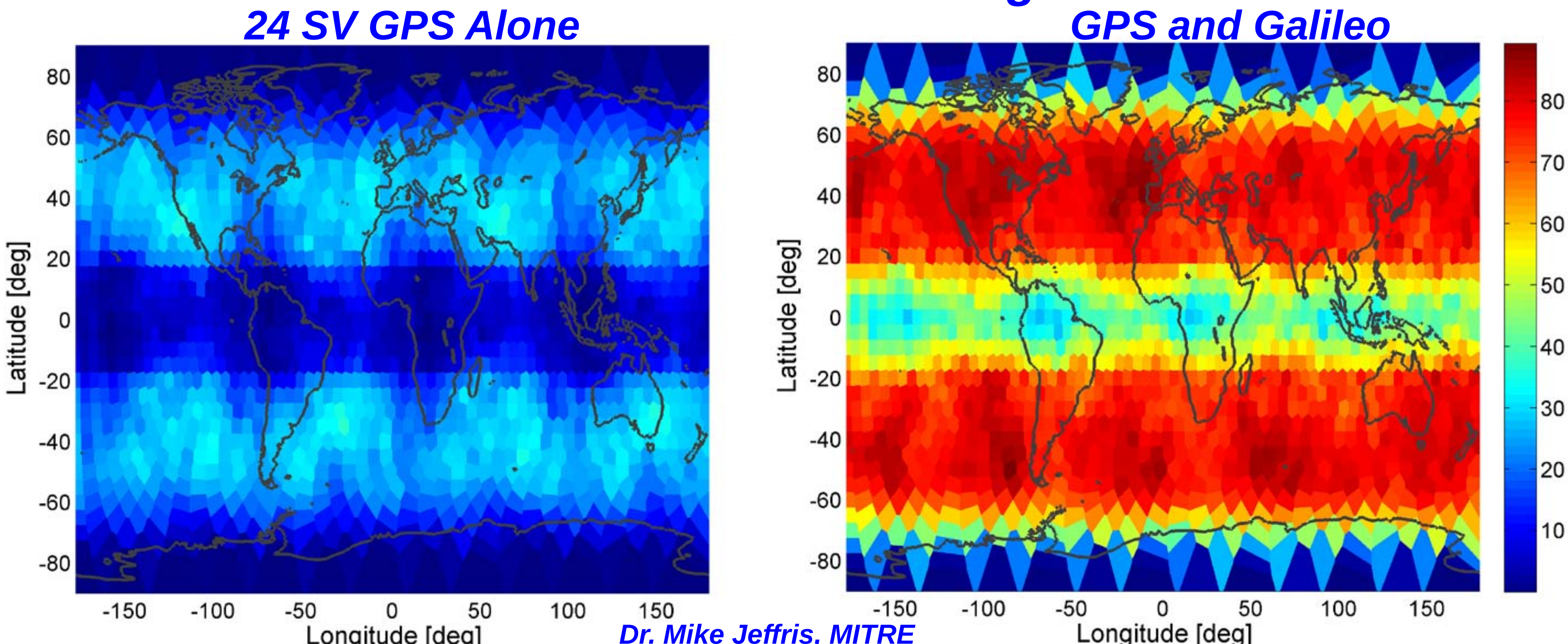
Close-Up View of Upper L Band



Future Space Segment: 100+ Satellites

- ***Why?:*** **Most constellations sized to provide standalone service from non-interoperable "authorized" signals**
- ***Benefit?:*** **Redundant measurements reduce DOP and enable receivers to reject invalid measurements**
- ***Benefit?:*** **Receivers with limited view of the sky**

Percentage of Time 4+ SVs Available and PDOP ≤ 10
Elevation Mask 45 Degrees



Dr. Mike Jeffris, MITRE

Receivers Define the Future

1981

2011

?

20XX

- **Milestone: U.S. 2005 requirement for E911 "location-capable" cellular telephones**
- **Development of receivers and augmentations has outpaced development of signals, satellites, and ground segments**

Ultimately, only capabilities and functions provided by receivers will affect users and services

Receivers Are Already Implementing the Future

GPS-extended

- **Satellite-based augmentations**
- **Integrated communications**
- **Other GNSS**
- **Signals of opportunity**
- **Local RF infrastructure**
- **Precision clocks**
- **Inertial sensors**
- **Vehicle wheel rotation sensors**
- **Compasses**
- **Barometers**
- **Pedometers**
- **Imaging sensors**

For the foreseeable future, satellite-based positioning and timing systems—and GPS in particular—will be the foundation for these extensions

Time Frames for GPS-Extended

- Now to 2020: refinement and diversification
  - Navigation and timing remains dominated by GPS, GLONASS, regional augmentations
  - Receivers incrementally add modernized signals and other extensions
- 2020+: full extension
  - Fully operational modernized capabilities on GPS and GLONASS
  - Fully operational COMPASS Phase 2
  - Fully operational Galileo
  - Enhanced sensors and other extensions

Challenges

- Dealing with uncertainty in schedule and capabilities for modernized and new satellite-based positioning and timing systems

- Selecting which new signals and systems to use
  - Move from parallel acquisition (one signal over delay and frequency) to hyperparallel acquisition (multiple signals over delay and frequency)

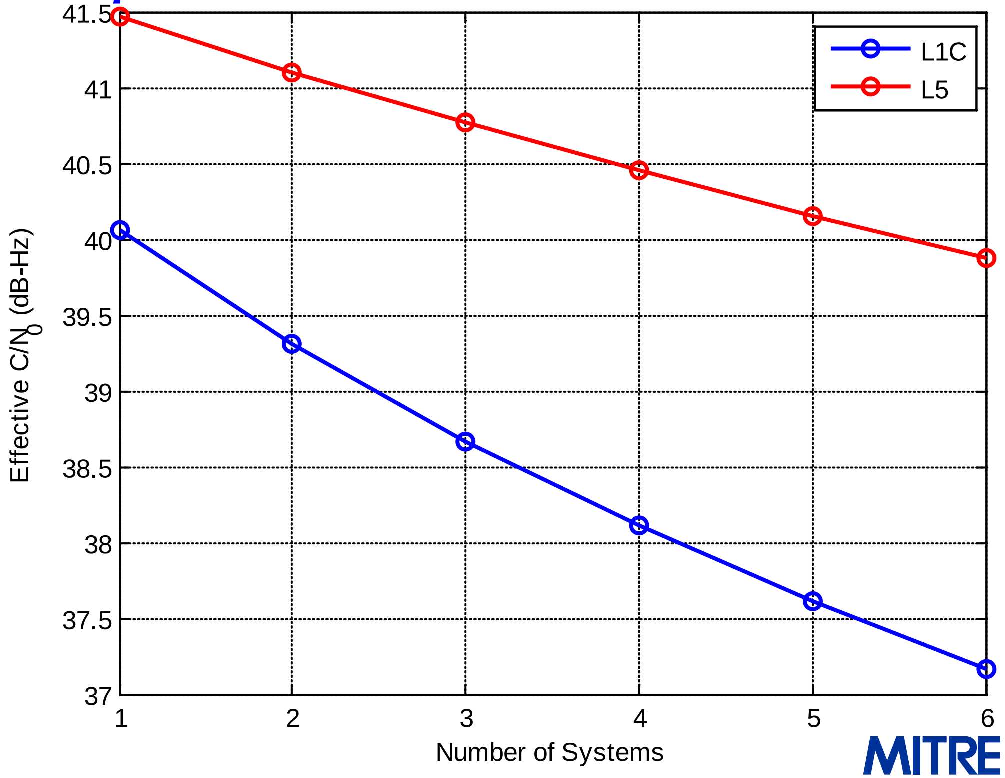
- Handling increasingly challenging user environments: heavy foliage, urban, indoor, deep indoor

- Operating in interference environments

Interference Considerations

- Intentional interference
- Interference in GNSS bands from other types of systems
- Adjacent-band transmissions
- Multi-GNSS interference

Example Calculation of Multi-GNSS Interference



- **Calculated using combined effects of thermal noise, nominal external interference, and multiple-access interference from other systems transmitting identical signals**
- **Neglects losses, receive antenna gain toward desired signal, interference from dissimilar signals**

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Promised Benefits of Modernized and New Systems

- Operation that provides even greater reliability and accuracy
- Multiple center frequencies
  - Correct errors from ionosphere
  - Frequency diversity
- More signals at common center frequencies
  - Geometry
  - Redundancy
  - Availability
- More capable signal designs
  - Robustness
  - Accuracy
- More capable receivers
  - Lower cost
  - Higher accuracy
  - More robust operation
  - Faster operation
- Signal specialization:
  - Safety of life
  - High-precision
  - Indoor
  - Mass-market
  - …

Summary

- There will be dramatic differences between satellite-based navigation 10 years ago and 10 years in the future
  - Number of systems
  - Number of satellites
  - Number of signals
  - Signal designs
  - System operations
  - Accuracy
  - Robustness
  - Receiver designs
  - *Integrated extensions to GPS*
  - Services
- The future will be driven by GPS-extended user equipment, with slower rollout of space and control segment improvements