Evidence for the Relativity of Simultaneity in Measured GPS Pseudo-ranges

Presentation at the

Global Positioning System Performance Analysis Working Group

Falcon AFB, Colorado, 23-24 August 1995

by

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"Fundamental Spacetime Experiments with Initial Emphasis on Investigations of Relativity and the Global Positioning System"

The Global Positioning System: A GRAND LABORATORY for the Application and Study of Special Relativity and Theories of Relativistic Gravitation

Analysis of Raw Pseudoranges, Calibration Experiments, and More Complete and Correct Physics Modeling can lead to:

- ◆ Higher Accuracy for GPS Users
- ◆ Better Comprehension of Subtle Concepts
- ◆ and, Possibly, New Knowledge of Physics

Research Tasks in Progress

1. Acquisition and Analysis of Existing GPS Measurements and Post-fit Orbits.
2. Laser Range Measurements to GPS and GLONASS Satellites while Receiving Pseudo-Range Data.
3. Experimental Investigation of the Isotropy of Local One-Way Light Propagation Times on the Rotating Earth.
4. Formulation and Computer Simulation of Improved Algorithms for the Modeling of Relativity

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Preliminary Report of Results of Task 1:
Acquisition and Analysis of Existing
GPS Measurements and Post-Fit Orbits

Examples use Space Command Monitor Station data for 23-24 August 1993 of GPS week 711 for SV 32 & SV 39 when Selective Availability (SA) encryption was turned off.

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Summary

- The relativity of simultaneity is the dominant correction needed to go from measured pseudo-range to geometric range.
- This fundamental effect of the special theory of relativity is not being modeled as such in the interpretation of monitor station data by the GPS control segment.
- Its inclusion should produce 1 m accuracy for authorized users in the standard mode.

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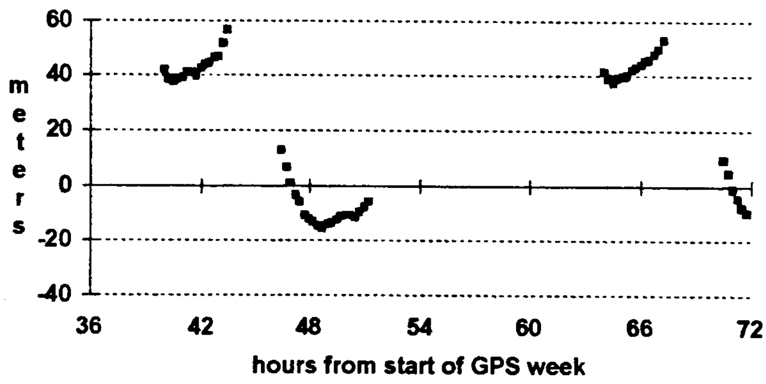
Procedure

- ◆Raw observed pseudo-ranges are compared with computed geometric ranges.
- ◆The contributions to these differences are shown for Hawaii - SV32 for, in turn:
  - Tropospheric Delay
  - Ionospheric Delay
  - Relativity of Simultaneity (Lorentz Time Transformation for Epoch of Transmission)

Hawaii - SV32

Observed pseudo-range minus Computed range (O-C)



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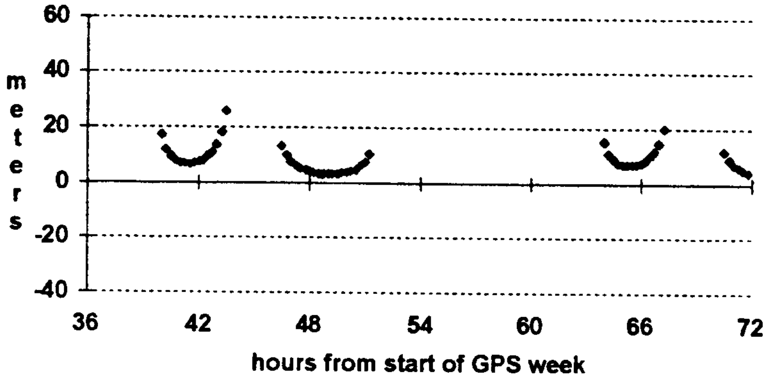
Details

- Observed pseudo-ranges are averages of 4 consecutive 1.5-second values within a single 6-second block.
- Computed ranges are geometric, using post-fit orbit state vectors provided by the Jet Propulsion Laboratory at 15 minute intervals, obtained by dynamically fitting to VLBI-type GPS observational data.
- Accuracy of orbits verified by laser range measurements to SV 35 and SV 36.

Details

- Estimated satellite and monitor station clock epochs and rates were initially supplied by the Naval Research Laboratory, based on clock monitoring by the Naval Observatory.
- These clock state parameters were then slightly adjusted to their best fit values over the 33-hour span of observations.
- No Change is made to these values during the entire data span.

Hawaii - SV32
Tropospheric delay



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Details

- Tropospheric delay calculations use a standard model, applying formula estimates for daily and seasonal variations in temperature, barometric pressure, and dew point from average figures for each monitor station.
- Air Force GPS monitor stations do not now measure these atmospheric parameters. They should do so!

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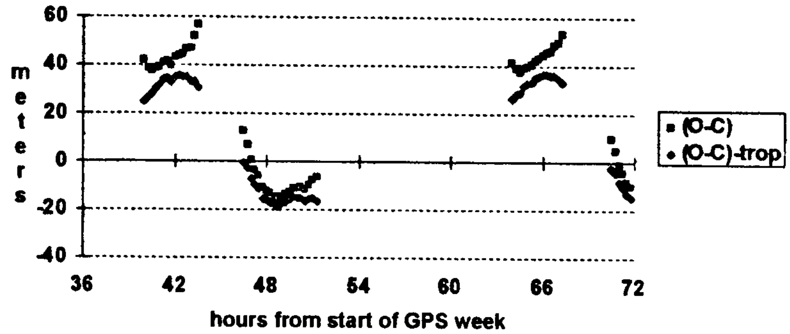
Hawaii - SV32
(O-C) corrected for tropospheric delay



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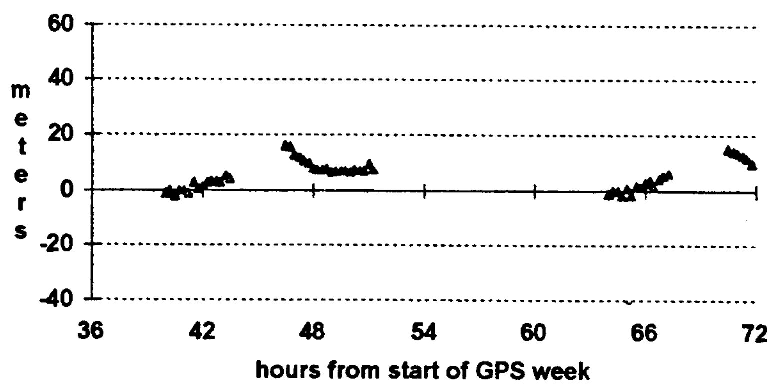
Hawaii - SV32
Ionospheric delay



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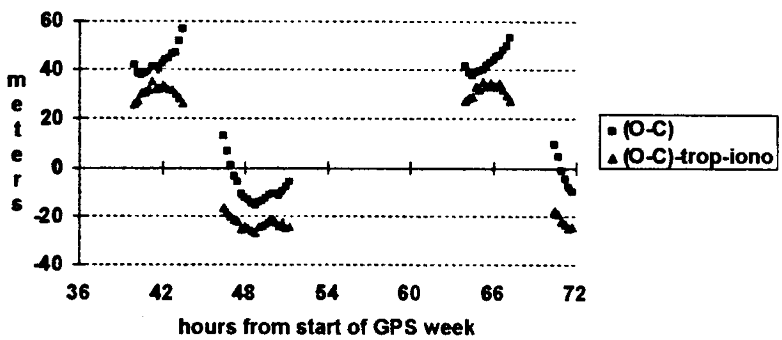
Details

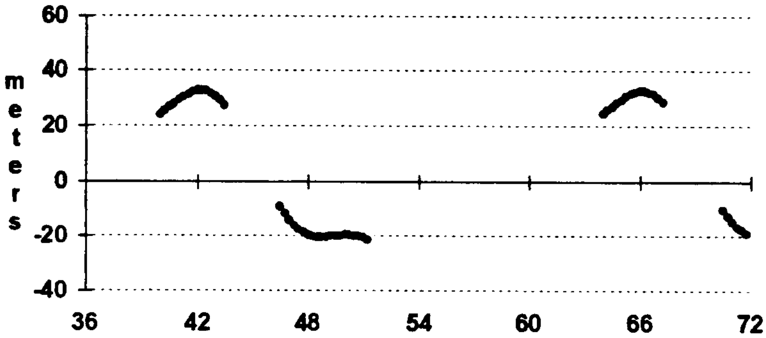
- Ionospheric delays are measured by observing the difference in pseudo-range values between the L1 and L2 frequencies, using knowledge of the dependence of the speed of propagation on frequency.

Hawaii - SV32

(O-C) corrected for tropospheric and ionospheric delays



Hawaii - SV32
Relativity of simultaneity effect

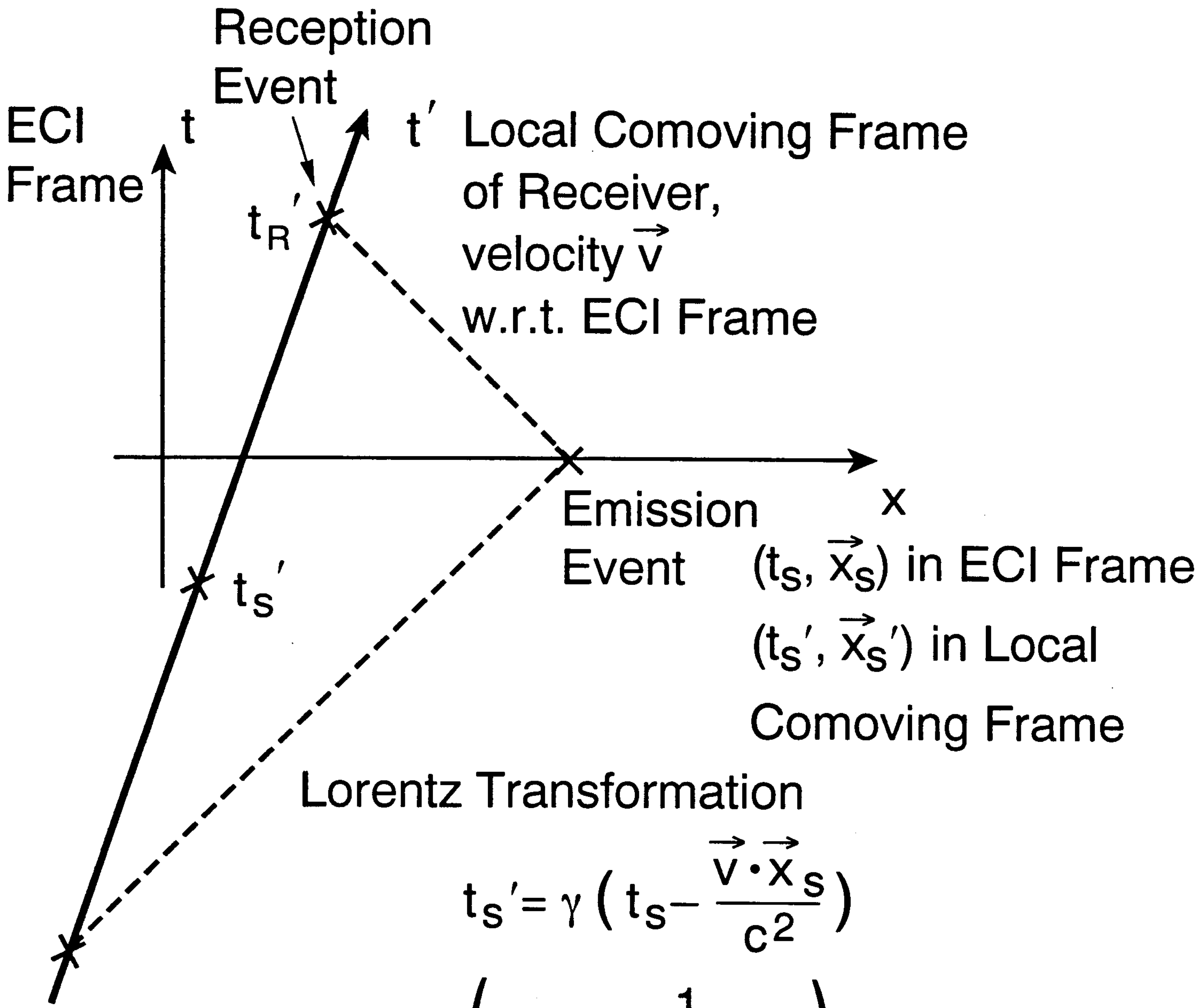


Details

- The relativity of simultaneity is given by the Lorentz time transformation for the epoch of transmission t, to be labeled as t' at the moving receiver. This ensures that the locally measured speed of electromagnetic waves in all directions is **c**.

$$t' = \gamma\left(t - \frac{\vec{v}_r \bullet \vec{r}_s}{c^2}\right)$$

Minkowski Spacetime Diagram



$$t_S' = \gamma \left(t_S - \frac{\vec{v} \cdot \vec{x}_S}{c^2} \right)$$

$$\left(\gamma = \frac{1}{\sqrt{1 - v^2/c^2}} \right)$$

Results

- (O-C) measurements, and their reduced values after allowing for delays and the relativity of simultaneity, are plotted for three different station - satellite pairs. Similar large reductions are obtained for all other pairs of monitor stations and satellites.
- The corrected rms pseudo-range residual for 19 satellites observed at all 5 monitor stations on these two days is ±2.6 meters.
- Station locations and SV ground tracks are shown above each plot.

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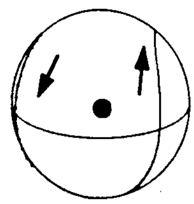
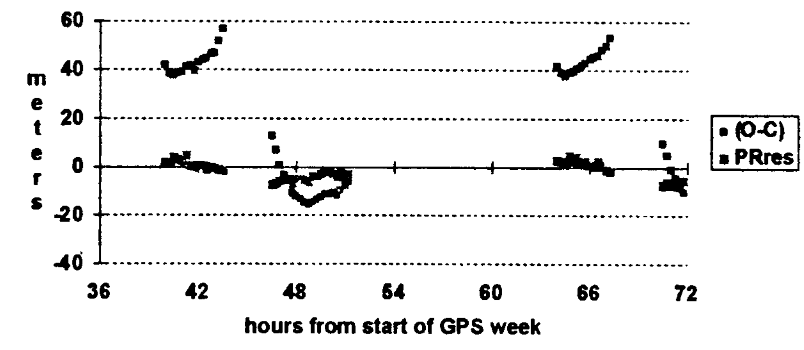
Lo W158
Lat +21

Hawaii - SV32

(O-C) & residuals allowing for delays and special relativity





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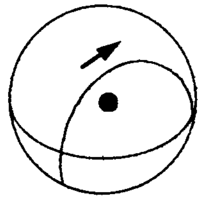
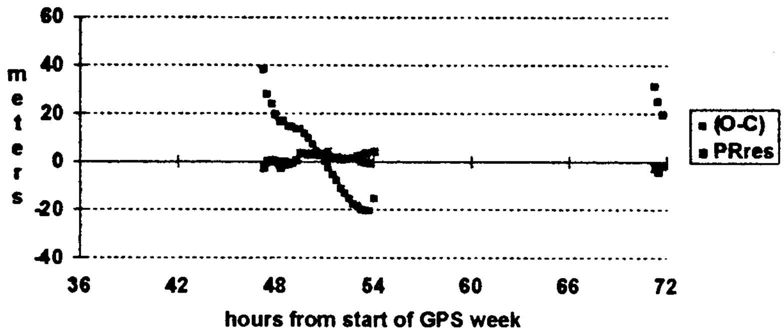
Lo W104
Lat +38

Colo.Springs - SV32

(O-C) & residuals allowing for delays and special relativity





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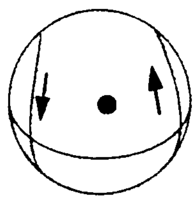
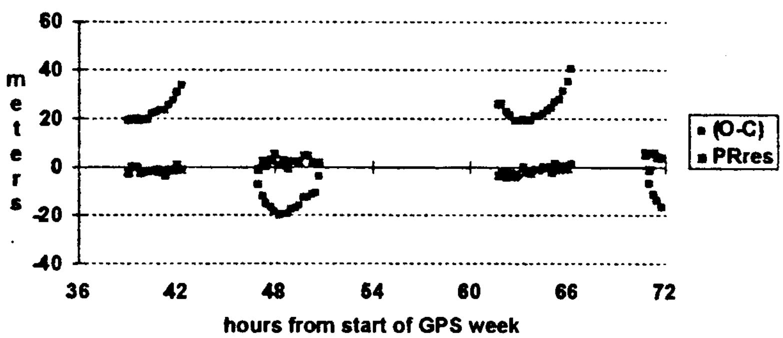
Lo W104
Lat +38

Colo.Springs - SV39

(O-C) & residuals allowing for delays and special relativity





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Space Vehicle 39

Corrected pseudo-range residuals
compared to uncorrected (O-C)s
for each of the 5 monitor stations
after allowing for tropospheric and
ionospheric delays and the
relativity of simultaneity

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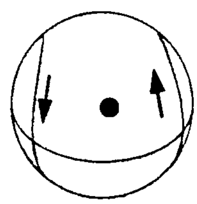
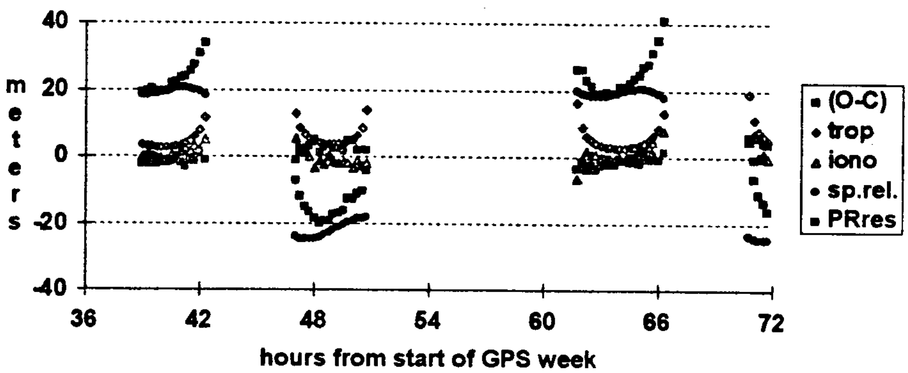
Lat +38

SV 39 from Colo.Springs



(O-C) & residuals allowing for
delays and special relativity



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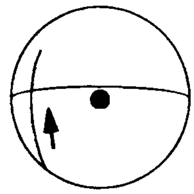
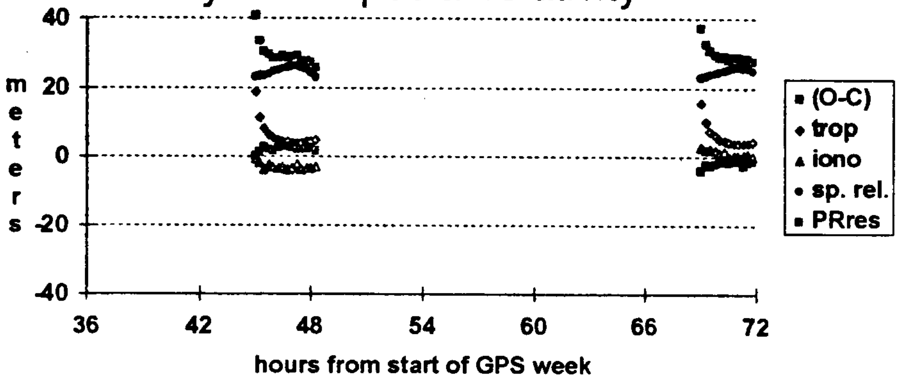
Lo W014
Lat -07

SV 39 from Ascen. Island



(O-C) & residuals allowing for delays and special relativity



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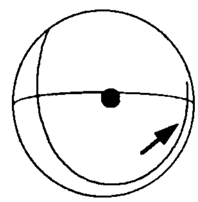
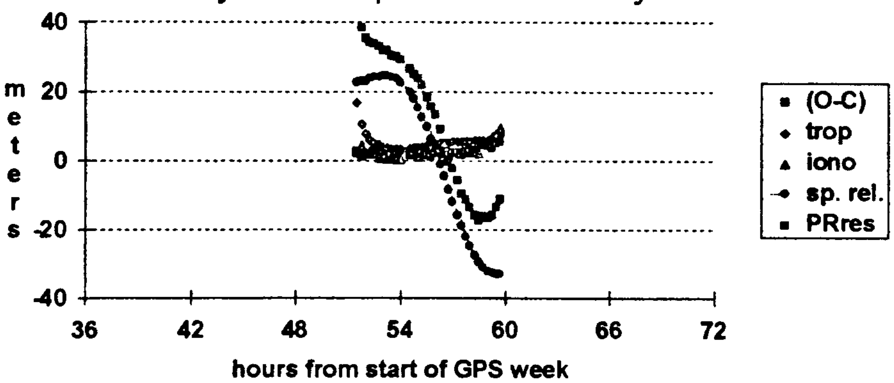
Lo E072
Lat -07

SV 39 from Diego Garcia



(O-C) & residuals allowing for delays and special relativity



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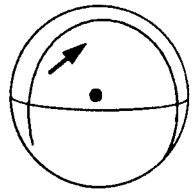
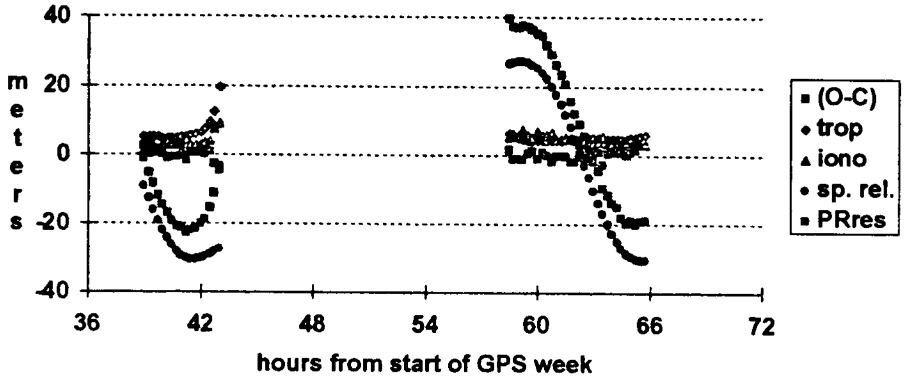
Lo E167
Lat +08

SV 39 from Kwajalein

(O-C) & residuals allowing for
delays and special relativity





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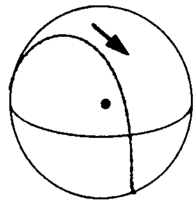
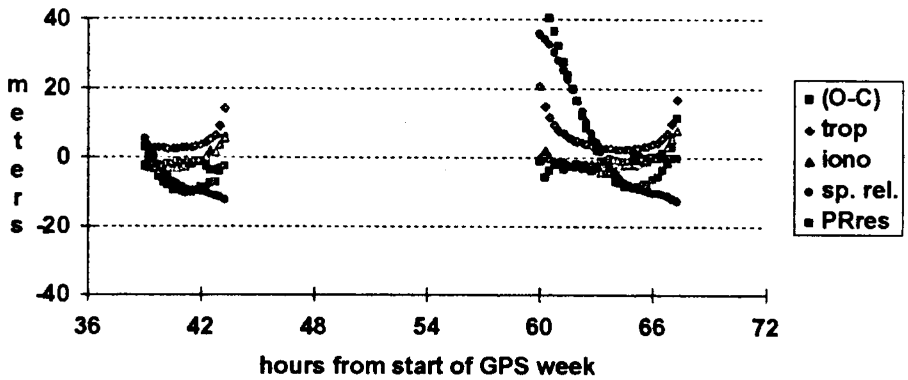
Lo W158
Lat +21

SV 39 from Hawaii

(O-C) & residuals allowing for
delays and special relativity





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Conclusions

- GPS monitor station receivers, measuring pseudo-ranges corrected in this way, could allow the assignment of orbital parameters and clock states with sufficient accuracy for authorized users to determine ground coordinates with an error ellipsoid radius of about 1 meter.
- Differential GPS to correct for systematic errors would not be needed for authorized standard mode users at this accuracy level.

End

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Y-AXIS = Completes a right-handed, earth-centered, earth-fixed orthogonal coordinate system, measured in the plane of the mean astronomic equator 90° east of the X-axis***

* Geometric center of WGS 84 ellipsoid

** Rotation axis of WGS 84 ellipsoid

*** X, Y axes of WGS 84 ellipsoid

??

20.3.3.4.3.4 Geometric Range. The user shall account for the effects due to earth rotation rate (reference Table 20-IV) during the time of signal propagation so as to evaluate the path delay in an inertially stable coordinate system. Specifically, if the user works in earth-fixed coordinates he should add $(-\dot{\Omega}_e y \Delta t,\ \dot{\Omega}_e x \Delta t,\ 0)$ to his position (x, y, z).

20.3.3.5 Subframes 4 and 5. Both subframe 4 and 5 are subcommutated 25 times each; the 25 versions of these subframes are referred to as pages 1 through 25 of each subframe. With the possible exception of "spare" pages and explicit repeats, each page contains different specific data in words three through ten. As shown in Figure 20-1, the pages of subframe 4 utilize six different formats, while those of subframe 5 use two. The content of words three through ten of each page is described below, followed by algorithms and material pertinent to the use of the data.

20.3.3.5.1 Content of Subframes 4 and 5. Words three through ten of each page contain six parity bits as their LSBs; in addition, two non-information bearing bits are provided as bits 23 and 24 of word ten in each page for parity computation purposes. The data contained in the remaining bits of words three through ten of the various pages in subframes 4 and 5 are described in the following subparagraphs.