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Two-Way Frequency Transfer via Satellite Using Carrier Phase

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1. Motivation to use Carrier Phase in TWSTFT Applications

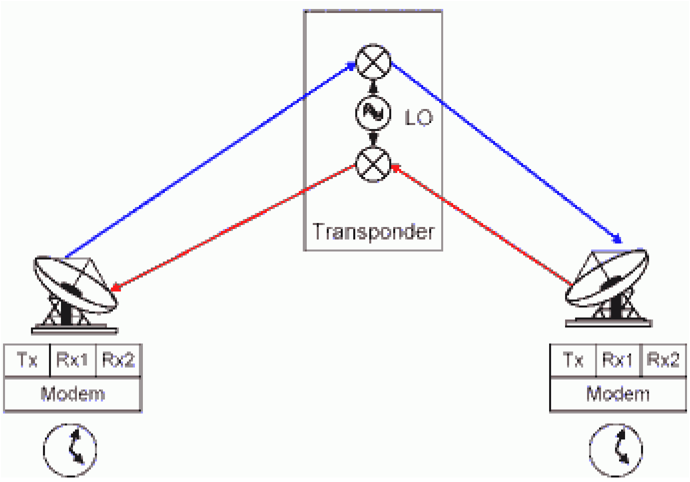
- 2.5 MChip/s PN coded signal used traditionally
- Higher chip-rates (20 .. 100 MChip/s) would improve precision and accuracy
- Existing installations may be limited due to available satellite transponder bandwidth
- Very encouraging results from GPS carrier phase and advanced processing software
- Competition factor: TWSTFT may have been seen at the 'performance limits'
- Design goal and expectation:
  1. Retain the proven and accepted properties of TWSTFT
  2. Improve frequency transfer precision (and accuracy?)

by factor of carrier-frequency / chip-rate . 400 … 4000

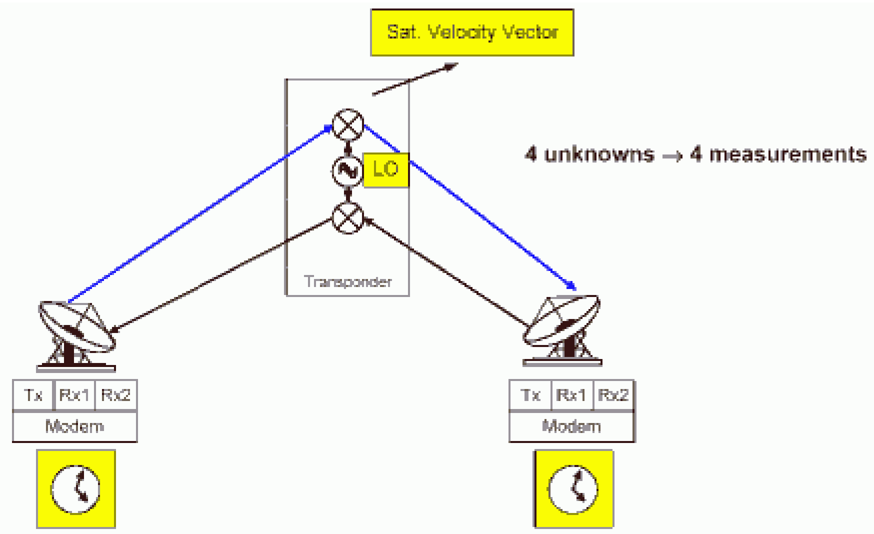
2. Typical Operational Scenario of TWSTFT

- VSAT Ground stations, transmitting and receiving at both ends
- Ku-band: 14 GHz uplink, 11.5 GHz downlink
- Chip-rate: 1...2.5...20 MChip/s
- Power: 1...5 W RF / 1.8 m antenna
- C/No: 40...60 dBHz ->noise 500ps (PN 2.5 MChip/s, t = 1s)
- Session duration: some minutes to reach noise floor
- Satellite properties
- Both stations see common transponder within footprint
- Different east-west transponders for large distances (Ku-band)
- But: Same local oscillator for all transponders, frequency: typ. 2 .. 2.5 GHz

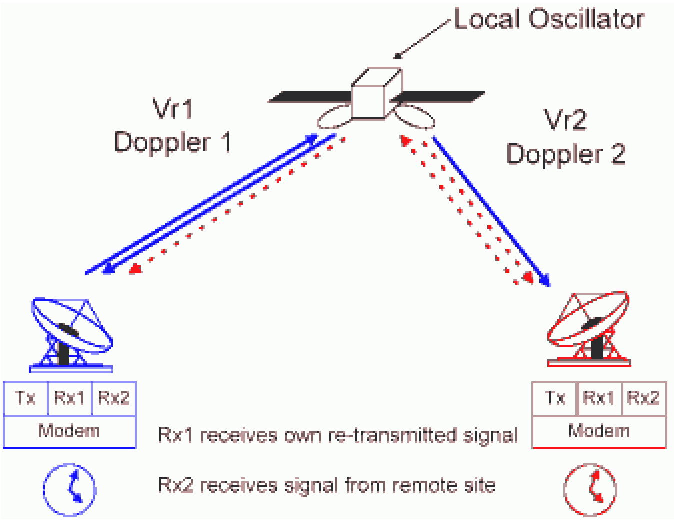
3. 'GEO-STATIONARY' satellite: Similarity to Dual Mixer System



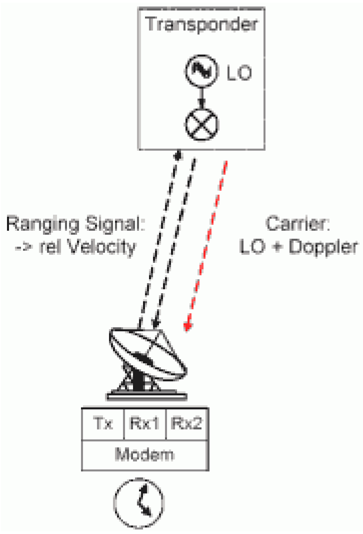
4. Error Sources and unknowns



5. Measurement configuration



6. Estimation of Satellite Local Oscillator Frequency



1. Receiver carrier measurement:
   Continuous counter referenced to local clock

2. Measure satellite LO frequency
   Perform code-based ranging to satellite
   Use same signals for code & carrier
   Determine satellite velocity (range-rate)
   Compensate down-link doppler

7. Error budget Satellite LO frequency by doppler compensation using range-rate

Carrier counter precision: 0.001 Hz (ô = 1s)
Thermal noise carrier: 0.003 Hz (ô = 1s)
Ranging noise: 3 .. 10 cm/s (ô = 1s)
Satellite LO uncertainty: 0.1 Hz or 4E-11
Measurement unaffected by

- Satellite location / direction of movement
- Transponder delay
- Ionosphere
- Troposphere

8. Summary and Outline of Algorithm

Solve for
1. Satellite LO frequency
2. Relative velocity to station 1
3. Relative velocity to station 2

4. Frequency error between ground clocks

- 4 independent measurements required (receive 2* remote signal, 2* own signal)
- But: no convergence (so far) on solution using the 4 carrier readings only
- Estimate satellite LO frequency
- Solve for the remaining 3 unknowns
- Show, that Satellite LO uncertainty has minor effect on result
- Far more complicated with respect to the straight forward 2-way formula

9. Frequency Transfer Uncertainties

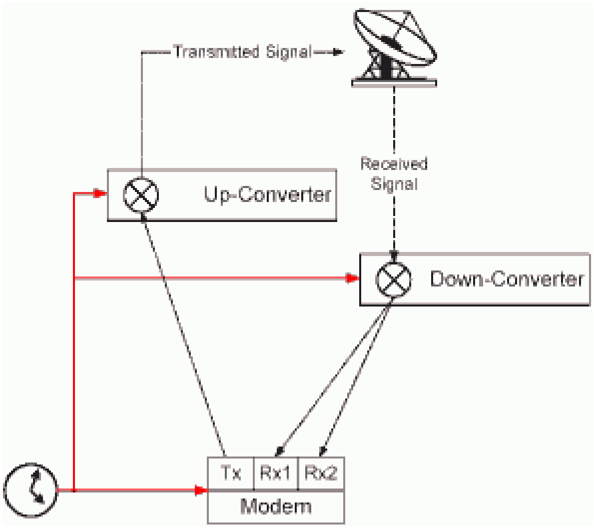
Omission of higher order clock-error terms: $(error)^2$ or typ. 1 E-28
Thermal receiver noise (0.003 Hz) 4 E – 14, ô = 1s, slope: sqrt(ô)
Satellite LO uncertainty: 4 E – 18
Sat. Location: none
Sat Velocity: 4 E - 18 (same as LO uncertainty)
Transponder: none
Troposphere: none (frequency independent)
Ionosphere: <300 ps / day (4 E-15), under pessimistic assumptions
asymmetry effect assuming absolute ion. delay of 50 cm in Ku band

10. Proof of concept

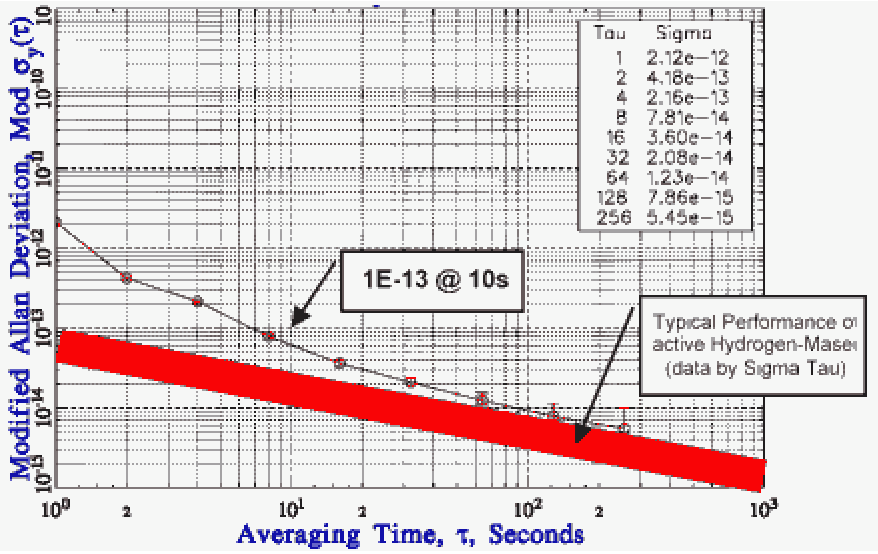
- Use different satellites with different LO (total 3 so far)
- Use different links between same clocks (USNO – NIST)
- Compare with known clock parameters
- Compare results with other time transfer means (TWSTFT, GPS CV etc)

Results from USNO – NIST test (2 active H-masers)
Frequency uncertainty few parts in 10-14 , ô = 20 min (PTTI 1999)
Noise 2*10-12, ô = 1s
Noise (PTB – DLR) 1*10-12, ô = 1s (EFTF 1999, 1 passive H-maser)

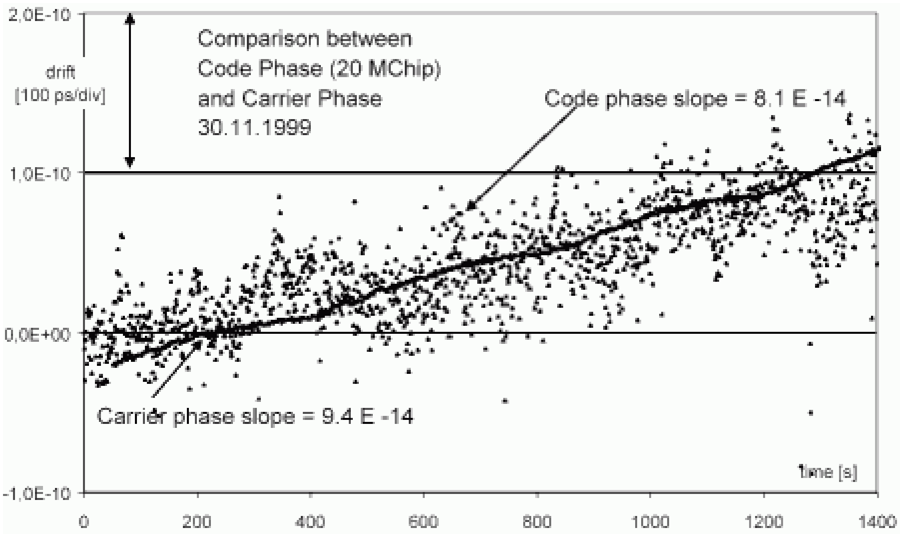
11. Ground Station Considerations



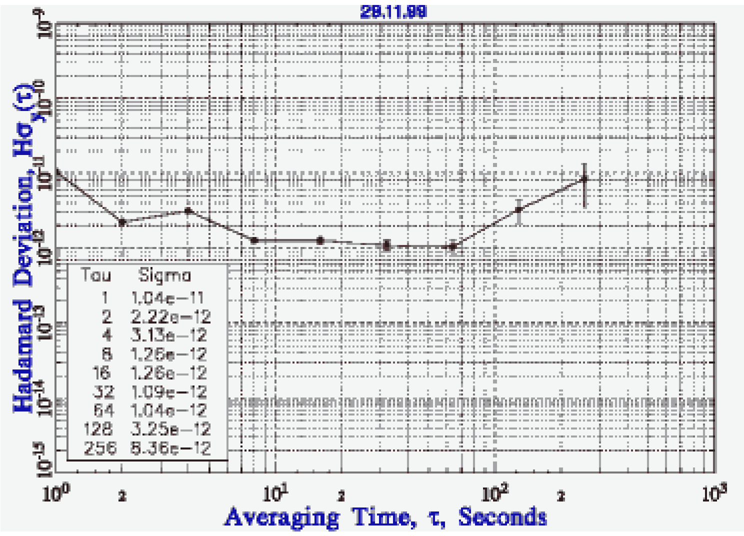
12. MDEV, Carrier Phase, Signal 2.5 MChip/s, USNO <-> NIST



13. Frequency Transfer, PN 2,5 and 20 MChip versus Carrier Phase



14. Satellite LO Characterisation



15. Conclusions

- Clear improvement of short term stability wrt code-phase by approx. 400 (ô = 1s)
- Short term stability (10 s < ô < 300 s) comes into the vicinity of H-masers
- Short term stability probably limited by station carrier frequency generation scheme
- Long-term stability (ô = 1 day) affected by link asymmetries (variation of ionosphere)
- Rigorous error assessment of TWSTFT and 2-way carrier phase
- Determination and elimination of errors due to link asymmetry
- Determination of satellite LO without transmission of a satellite-generated signal
- More in-depth analysis required, convergence of algorithm, real-time calculations
- USNO, NPL & PTB are setting up installations