Conclusive analysis & cause of the flyby anomaly

Range proportional spectral shifts for general communication

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Summary

- Popular context: Astrometric solar-system anomalies[1]
    - Pioneer: $\Delta V \sim \dot{r} \approx -H_0 r$ at $r \geq 5\ \mathrm{AU}$ (blueshift) – SOLVED[2]
    - Flyby: ΔV trajectory discontinuity at satellite range
    - Lunar orbit eccentricity growth: also $\sim H_0$ [3]
    - Earth orbit radius growth: also $\sim H_0$
- Present work: conclusive solution of the flyby anomaly
    - All NASA-tracked flybys checked, fit to 1%, more issues found
    - Fit presence *and* absence, correlated to transponder
- Real motivation and result: wave theory+practice correction
    - Rewrite communication and radar: source range in *all* signals
    - Rewrites physics and astrophysics since Kepler
    - Computation overlooked since Euler and d'Alembert
    - Needed extremely robust empirical validation

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[1] Anderson and Nieto 2009.

[2] Turyshev et al. 2012.

[3] The terrestrial reference frame is uncertain to about same order..Altamimi et al. 2016

Faithful led by the blind

- Fourier transform presumes clock rate stability
  - Clock rate stability requires design and procedures
  - But even HST calibration cycles only correct *cumulative* errors
    - No awareness of range proportional or scale drift rate errors
    - *Best* Allan deviations in *any* observations are $o(H_0)$
    - What if drift rate errors ⇔ $O(H_0 r)$ shifts – Hubble's law!
- Translational invariance is *selective*
  - If only phase can change, $d\psi(t)/dt = i\omega\psi$, so $\psi(t) = e^{i\omega t}$
    - Sinusoidal waves historically *preconceived*
    - For vibrational modes under static boundaries
  - Chirp *transforms* are known, what prevents their spectra?
    - Chirps are *translationally variant* ⇔ Hubble-like shifts
    - We don't need a contrived metric, any more than angels
- Translational invariance constrains *analysis* instead of *physics*
  - FM, Doppler rate = continuously varying frequency $\dot{\omega}$
  - Current *analyses* assume Fourier: $\dot{\omega} = 0$
  - The flyby anomaly is *nature* saying they are incomplete

Engineers need to pave the way

- Translational *variance* is *fantastically useful*[4]
  - Spectrum no longer a limited, shared resource
  - Every receiver can be physically unjammable
  - Instant triangulation – no need for range codes, many radars
- d'Alembert equation notoriously factors *unconditionally*
  - Wave equation admits (whole dimension of) *expanding* solutions
  - We just didn't have a way to observe, access them
  - Optical diffraction gratings, prisms are rigid $\sim$ enforce invariance
- Spectral analysis and selection are *macroscopic functions*
  - Correspondence Principle is a Zeno's Paradox *and* a Red Herring
  - The kernel is always physical, macroscopic and continuously variable
  - Especially in radio receivers: local oscillator (LO)
- Chirp spectra are translationally *variant*
  - Components $\exp(i\omega_0 e^{\beta[t-\Delta t]}/\beta) \Leftrightarrow$ shifts $\Delta\omega = -\omega\beta\Delta t$
  - Don't really depend on $r \Rightarrow$ wave notions are irrelevant!

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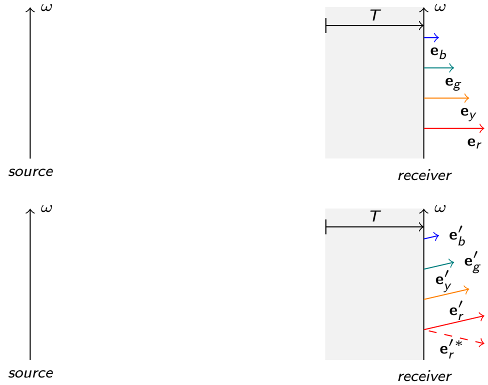
[4] Guruprasad 2005.

Spectra are computed representations $_1$



The representation defines component shifts, like an oblique coordinate grid.

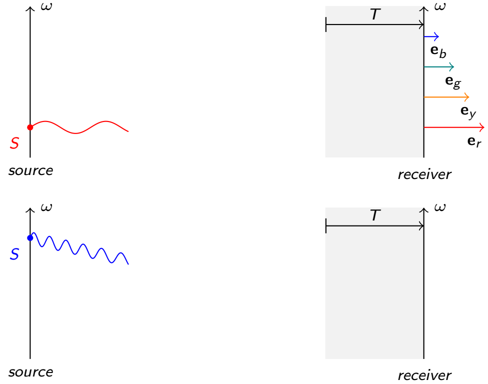
Any FM in Fourier basis

- Discontinuous in ω
- Pieces *violate* d'Alembert!
- Velocity $\dot{\omega}$ *unrepresentable* vanishes in ideal FT

Steady tone in chirp basis

- d'Alembert with $\dot{\omega} \neq 0$
- Zero Fourier amplitudes!
- Requires chirp basis – basis itself has velocity $\dot{\omega}$

Spectra are computed representations 2



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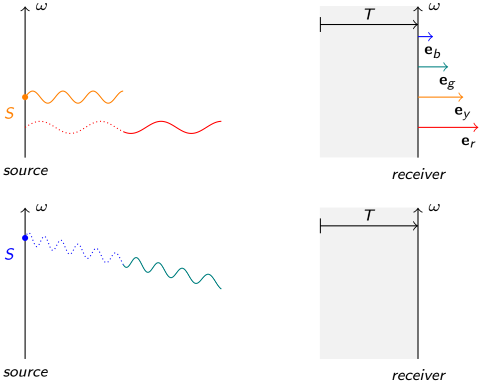

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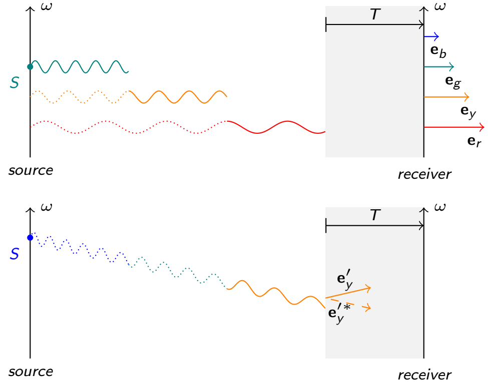

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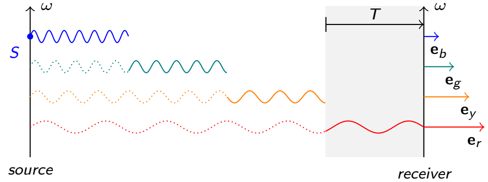

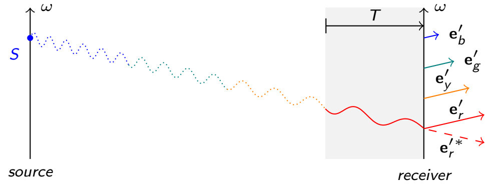

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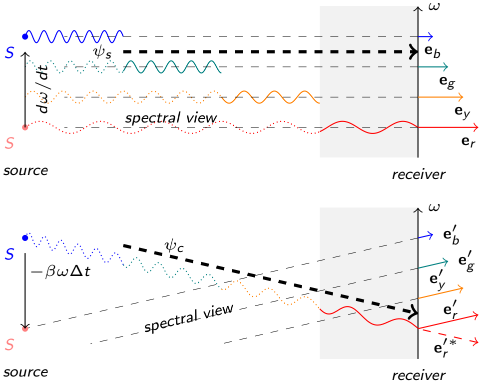

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  this is a *power* signal

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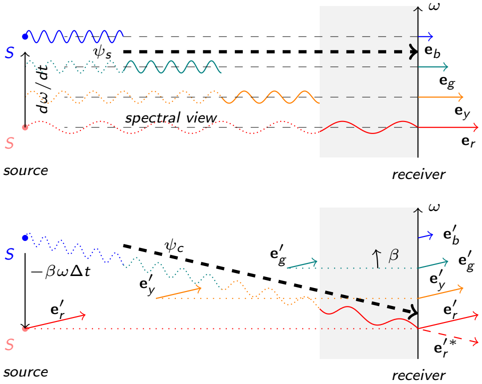
- Inclined view with shifts

Spectra are computed representations [7]



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- Inclined view with shifts
- A *group* under translations
  (so Fourier is *degenerate*)

The many challenges on the way

- Spectral connection to instrument scale variation was unclear
  - Scale unit μ, target interval L, measure is L/μ
    A drift rate $\dot{\mu}$ must add $-\dot{\mu}.L/\mu^2 \equiv -\beta L$ to velocities
    But why would the virtual velocities have Doppler shifts?
- Time derivative of wavelength comb radar imaging[5]
  - No fast continuously variable gratings for off-the-shelf optical test
  - Lacked "empirical authority" for confidence on chirp spectra
  - Made no sense to physics colleagues either (with Fourier view)
- Rigidity solvable in radio receivers, but
  - Analogue is still rigid hardware & digital sampling rejects chirps
  - Basic questions, besides time and cost, against experimenting:
    What β is critical, how long to ramp? (limits components)
    What signals to seek? Does it need "FM content"?
  - Fortuitously answered by NASA, US STRATCOM, and ESA

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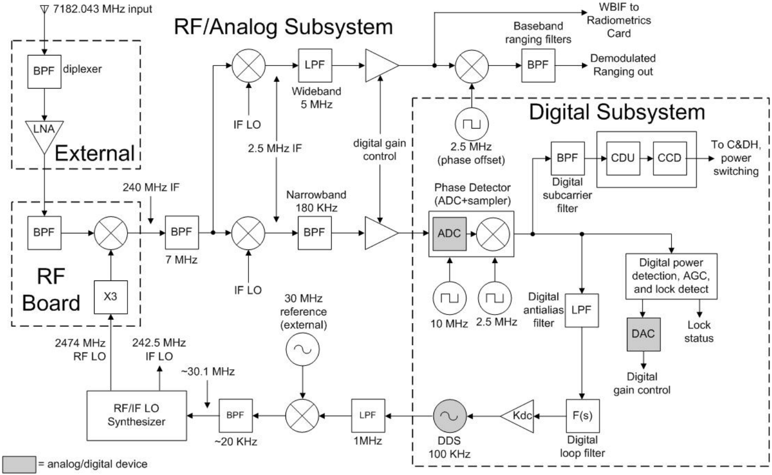
[5] Guruprasad 2005.

Modern, non-phase lock receiver (after Cassini)[6]

$$\int_T \exp(i\omega_0 e^{\beta[t-r/c]}/\beta) \times \exp(-i\omega_{x0} e^{\beta' t}/\beta')\, dt$$



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[6] Chen et al. 2000; DeBoy et al. 2003.

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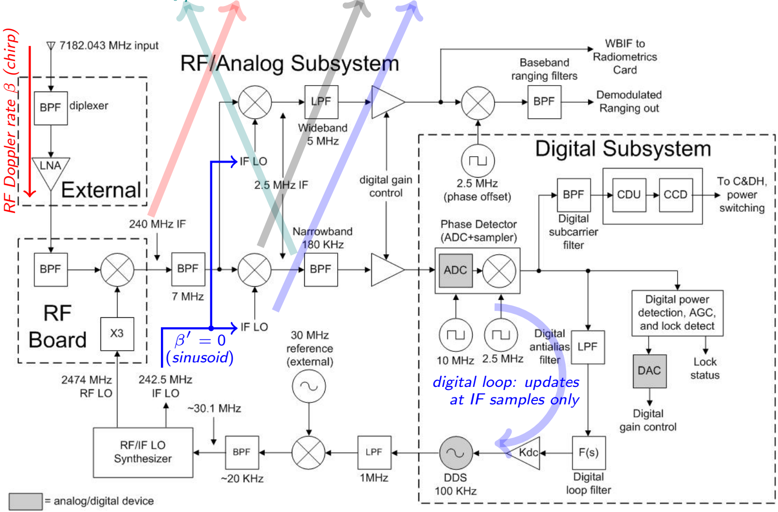

RF Doppler rate β (chirp)

$\beta' = 0$ *(sinusoid)*

digital loop: updates at IF samples only

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[6] Chen et al. 2000; DeBoy et al. 2003.

Transponder phase lock loop (Galileo, NEAR, Cassini)[7]

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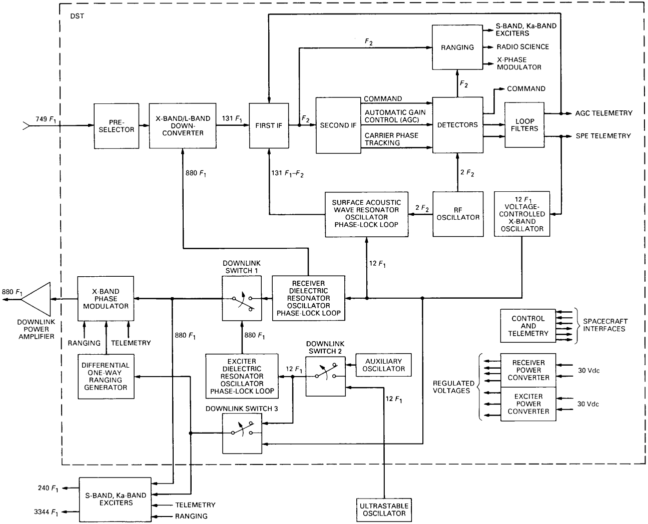

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[7] Mysoor, Perret, and Kermode 1991; Bokulic et al. 1998; Chen et al. 2000.

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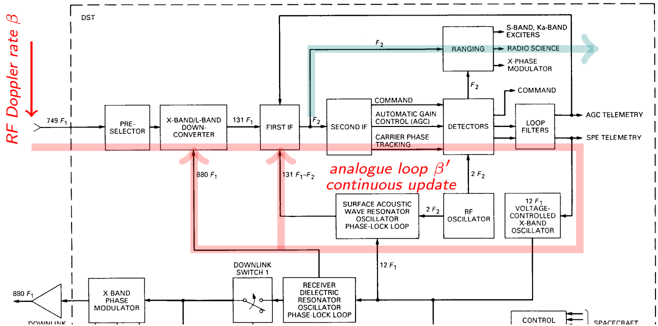

- Red path: carrier phase-locked loop, teal path: signal
  - Phase error *value* is typically digital – using logic gates
  - Analogue *in time* ⇒ phase error is detected *continuously*

  ⇒ resonators track each RF cycle

  ⇒ carrier Doppler, demodulated signal from chirp spectrum

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[7] Mysoor, Perret, and Kermode 1991; Bokulic et al. 1998; Chen et al. 2000.

Opportunity in the flyby data

- The distinct circumstances in Earth flybys (and NASA)
  - Sustained Doppler rate $\beta > 0$ in approach, $\beta < 0$ in retreat
  - Tracked by 2-way Doppler of telemetry carrier
    Requires dedicated DSN (or ESTRACK) antennas
    Even geostationary satellites do not merit this
  - Non-repeating and used for subsequent mission calibration
    so any lag or advance in Doppler stands out
  - NASA started with phase lock transponder, and published data
    ESA only due to NASA role, no data for JAXA, other countries

- Signature of the chirp mode in the flyby data
  - SSN residuals fit range lags: $\Delta r = -v\Delta t,\ \Delta t = r/c$
  - Anomaly fits velocity lags: $\Delta v = -a\Delta t,\ a \equiv \dot{v}$
  - Velocity lags $\Delta v \Leftrightarrow$ Doppler lags $\Delta\omega = \dot{\omega}\Delta t$
  - Identical in sign, magnitude to CWFM but in excess

The tracking and the anomaly

- Deep space tracking using telemetry
  - PN codes (initial range) + Doppler integration (fine range)[8]
  - Precise enough for general relativity tests[9]
- Velocity discrepancies ΔV across gap in tracking[10]
  - Galileo 1990: 4.3 $\mathrm{mm/s}$
  - NEAR 1998: 13.46 $\mathrm{mm/s}$
  - Rosetta 2005: 3.6 $\mathrm{mm/s}$[11]

    Reported as 1.82, tracking resumed *before* perigee[12]
- Limitations of the JPL definition
  - If there is no gap, ΔV cannot manifest (Cassini)
  - Trajectory can be dynamically wrong even with $\Delta V = 0$
  - ΔV is a computed error $\not\Rightarrow$ real force/energy at orbit range

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[8] Anderson, Laing, et al. 2002.

[9] Bender and Vincent 1989.

[10] Antreasian and Guinn 1998; Anderson, Campbell, et al. 2008.

[11] Morley and Budnik 2006.

[12] T Morley (2017). Pvt comm.

Other symptoms

- Perigee shift relative to target at last control manoeuvre
  - NEAR: $+6.8$ km change in altitude (NASA press releases)
  - Rosetta 2005: -340 ms (advance, ~ 10.2 km)
    Compare: Juno: $+0.26$ ms[13][14]
- Large residual swings
  - Around perigee (Galileo[15], Rosetta[16])
  - Large diurnal oscillations post-perigee (NEAR[11][17])
- Large range errors against SSN radars (NEAR[11], Galileo[18])
  - Up to 1 km $\sim 100\times$precision, $\gg 5\sigma$[19]
  - Yet JPL thought it was "noise"[14], buried in AIAA 1998!

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[13] Thompson et al. 2014.

[14] P F Thompson (2019). Pvt comm.

[15] Antreasian and Guinn 1998.

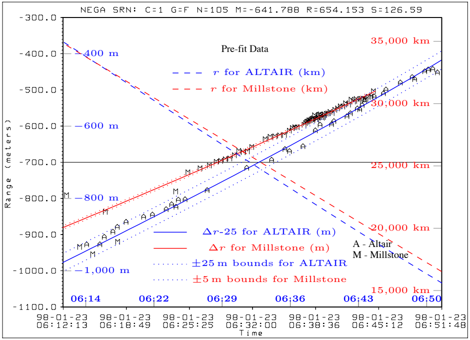
[16] Morley and Budnik 2006.

[17] Anderson, Campbell, et al. 2008.

[18] J K Campbell (2015-). Pvt comm.

[19] P G Antreasian (2017). Pvt comm.

NEAR's SSN radar range residuals: errors Δr



- Against integrated telemetry Doppler range
  - Too *systematic* for circuit fluctuations: $R/S > 5\sigma$
  - Too *large* for random error: 40ϵ Altair, 140ϵ Millstone
  - Too *large* for transponder latency: error $\Delta t = 60\text{-}140\ \mathrm{ms}$
- $\Delta t =$ one-way "light times"[a] r/c, whence $\Delta v = -ar/c$

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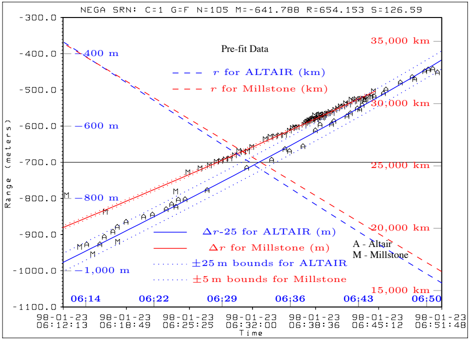
[a] Guruprasad 2015a.

NEAR's SSN radar range residuals: the choices



- Physicists' interpretations
  - Blame radar (JPL physics) ⇒ DoD's SSN *superluminal* at $2c$[a]
  - Source-dependent c (EPL comment) $\sim$ telemetry at $c/2$
- Concede JPL's graph *already* shows $\Delta\omega = -\omega H r$ in Doppler
  - Hubble's law with $H = \beta/c$, β: fractional Doppler rate $\sim 10^{-6}/\mathrm{s}$

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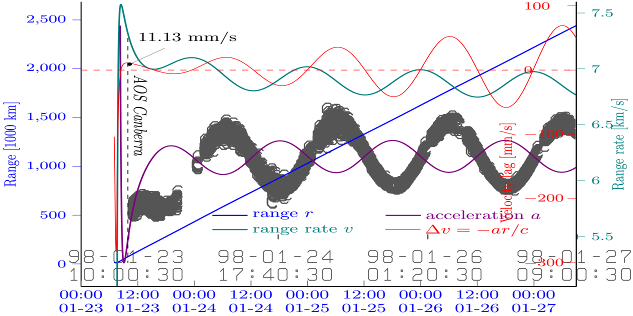
[a] Since Δt is the full one-way light time

NEAR perfect fit: $\Delta v \simeq \Delta V$ – post-encounter (Canberra)



- $\Delta v \equiv -ar/c = 11.13\ \mathrm{mm/s}$ at AOS $\sim$ 20% of anomaly[a]
- Correlation with $\Delta v \Rightarrow$ JPL's direction prediction issue[b]
- Impossible growth in v (range rate from JPL Horizons)

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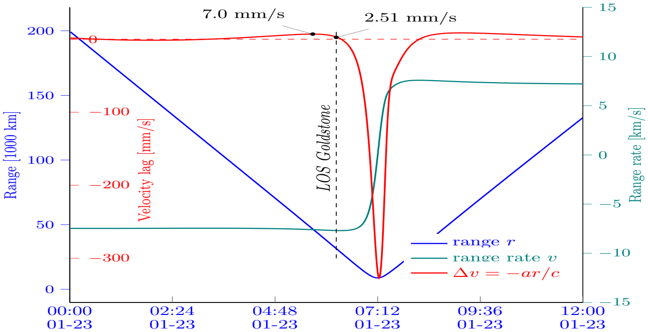
[a] Guruprasad 2015a.

[b] Anderson, Campbell, et al. 2008.

NEAR perfect fit: $\Delta v \simeq \Delta V$ – pre-encounter (Goldstone)



- Balance of Δv found at LOS
- Total $\Delta v = 11.13 + 2.51 = 13.64$ mm/s
- Result is 1.3% of $\Delta V = 13.46$ mm/s[a]

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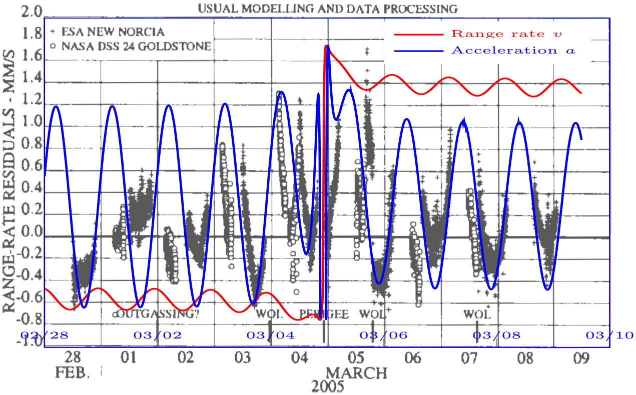
[a] Anderson, Campbell, et al. 2008.

Explaining Rosetta 2005 residuals



- Large residuals ⇒ Doppler not following range rate
- Consistency with velocity lags ⇐ residuals follow *acceleration*
- Broken residual tracks: fresh acquisition every day
- New Norcia track consistently follows acceleration

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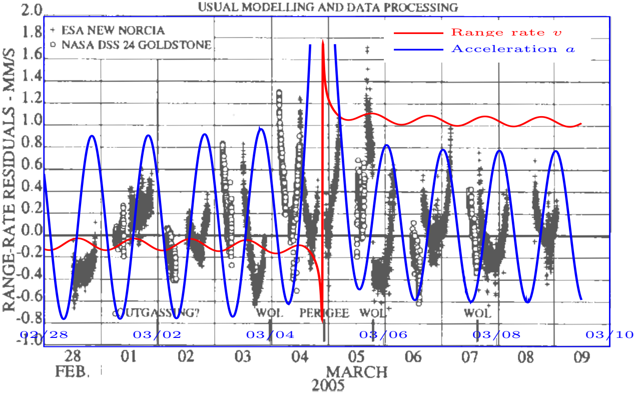
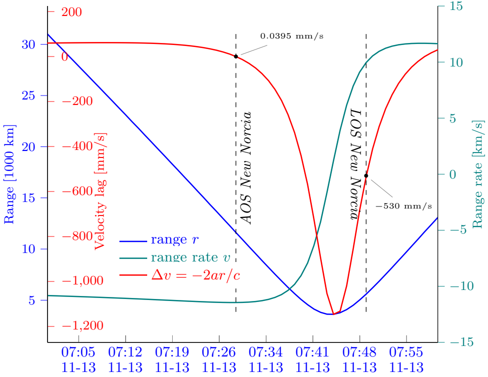


- Large residuals ⇒ Doppler not following range rate
- Consistency with velocity lags ⇐ residuals follow *acceleration*
- Broken residual tracks: fresh acquisition every day
- Goldstone tracks acceleration till 05, even “outgassing” on 01

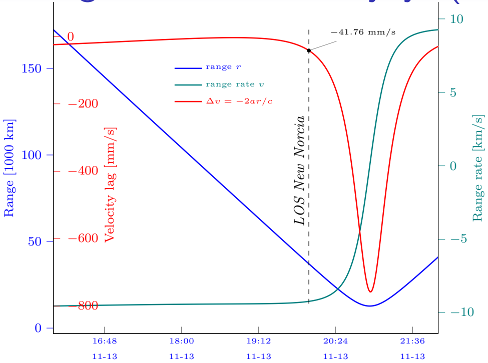
Explaining Rosetta's later flybys (2009)



2009 : both LOS, AOS at New Norcia

- $\Delta v_{AOS} \approx -530\ \mathrm{mm/s} \sim 15\ \mathrm{Hz}$ – way outside loop filter band
- $\Delta v_{LOS} = 0.0395\ \mathrm{mm/s} \sim 1\ \mathrm{mHz}$ – indistinguishably small
- Consistent with no anomaly

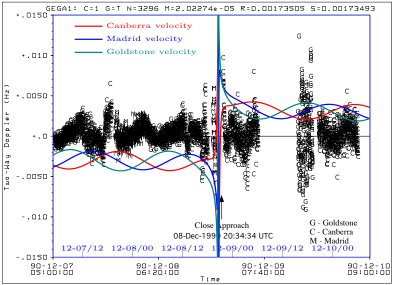
Explaining Rosetta's later flybys (2007)

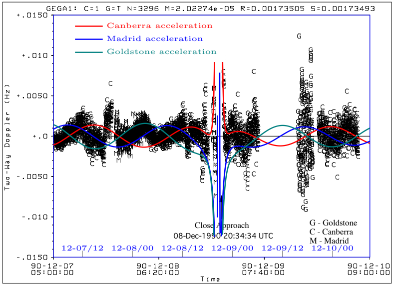


2007 : LOS at New Norcia, AOS at Goldstone

- $\Delta v_{AOS} \approx -514\ \mathrm{mm/s} \sim 14\ \mathrm{Hz}$ – way outside loop filter band
- $\Delta v_{LOS} = -41.76\ \mathrm{mm/s} \sim 1.2\ \mathrm{Hz}$ – also outside loop band
- New Norcia likely *acquired* Fourier mode much earlier

The cold case of Galileo 1990[20][21]





- Goldstone residuals follow velocity late on the 9th
  $\Rightarrow$ unlikely to have caused anomaly
- Canberra residuals follow acceleration around C/A
  $\Rightarrow$ most likely cause of anomaly
- Start/end times too imprecise this close to C/A for Δv-ΔV fit

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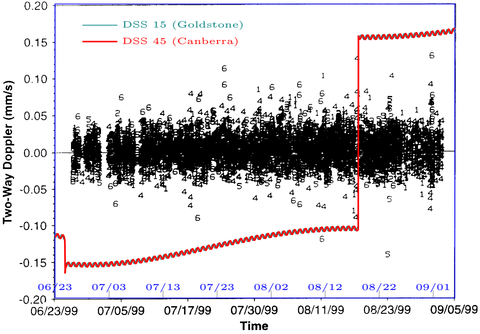
[20] Antreasian and Guinn 1998.

[21] P G Antreasian (2017). Pvt comm.

Continuously tracked: Cassini[22]



- Continuously tracked by multiple stations (watched pot!)
  - ⇒ dragging even by large Δv gets averaged out
  - ⇒ spikes could be chirp lock at AOS, but too small
- No tracking gap ⇒ no possibility of ΔV discontinuity

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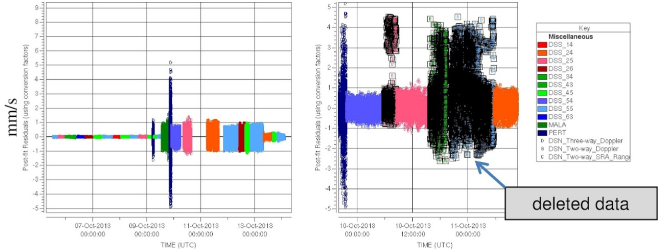
[22] Guman et al. 2000.

Non-phase lock: Juno[23], MESSENGER[24]



deleted data

- Juno residuals (above) comparable to Rosetta's
  - But entirely consistent with multi-path reflections under spin
  - "Deleted data" – tracks excluded for very large spin issues
  - No anomaly consistent with non-phase locking:
    - Tracks not overlapping but agree on trajectory: no Δv
    - Perigee shift: $+0.26\ \mathrm{ms}$, *versus* $-340\ \mathrm{ms}$ for Rosetta
- MESSENGER residuals $\sim$ Cassini's: $0.15\ \mathrm{mHz}$ – no anomaly

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[23] Thompson et al. 2014.

[24] J K Campbell (2015-). Pvt comm.

Onward and outward

- We are *truly* done with the flyby anomaly
  - *All* flybys analyzed where anomaly details and data available
  - Only exclusions – all non-NASA and
    Galileo 1992 (uncertain anomaly, no AOS/LOS details)
    Stardust, DI/EPOXI[25], OSIRIS-REx (no anomaly, details)
  - Requested and overseen by J K Campbell of "JPL anomaly team"
    Team noted consistent absence of anomaly since Cassini
    Campbell noticed correlation with transponder change
- Chirp mode evidence is most robust observations of mankind
  - Trajectory fits verify consistency – ΔV fit meaningless beyond 1%
  - Direct evidence is NEAR's SSN residuals
    - Millstone data is 100σ : overall 5σ ignoring independence
    - Astrophysics, particle physics *less robust* on Allan deviations
- Chirp mode receivers would be simple, immensely significant
  - Sawtooth FM of LO[26] – POC challenge is LO signal conditioning

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[25] Bhaskaran et al. 2011.

[26] Guruprasad 2015b.

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