IGS Reference Frames: Status & Future Improvements

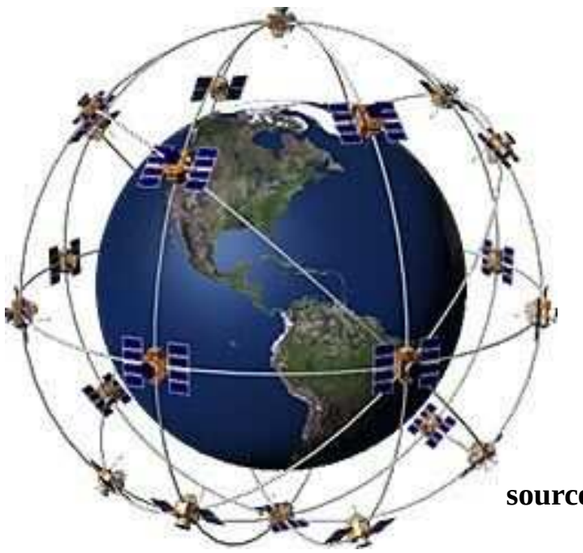
Jim Ray, Bureau International des Poids et Mesures & National Geodetic Survey

Danan Dong, Jet Propulsion Laboratory

Zuheir Altamimi, Institut Géographique National

- **Hierarachy of IGS Reference Frames**
- **Handling of Non-Linear Variations**
- **Improvements in Analysis Center Procedures**
- **IGS Combination Procedures**
- **Improvements in ITRF**
- **Improvements in IGS Reference Frames**
- **Summary of Recommendations**

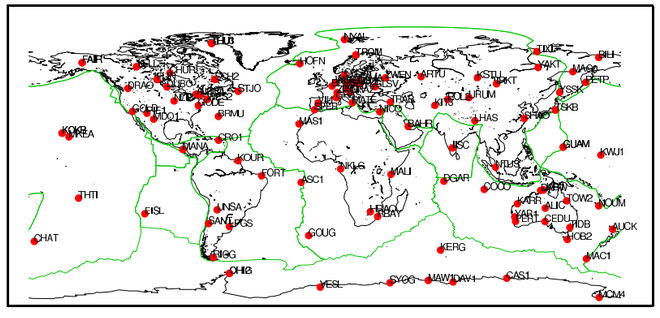
Hierarachy of IGS Reference Frames



source: Garmin

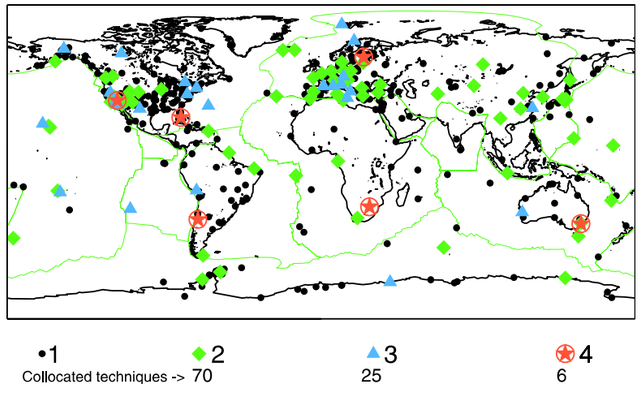
User access level – IGS “instantaneous” frames

- precise point position (PPP) with fixed IGS orbits & clocks
- does not depend directly on any fiducial stations
- can be applied anywhere/anytime
- gives access to IGS00/ITRF at cm level for 1 d of data



Secondary precision layer – IGS00 long-term frame

- aligned to ITRF2000 datum for 99 high-quality stations
- used for all IGS products instead of ITRF directly
- internal consistency much better than ITRF
- permits highest self-consistency for IGS products



Foundation accuracy layer – ITRF2000 long-term frame

- “absolute” datum: origin, scale, orientation & their rates
- combination of SLR, VLBI, GPS & DORIS global solutions
- ∼800 points at ∼500 sites

Reference Frame Errors

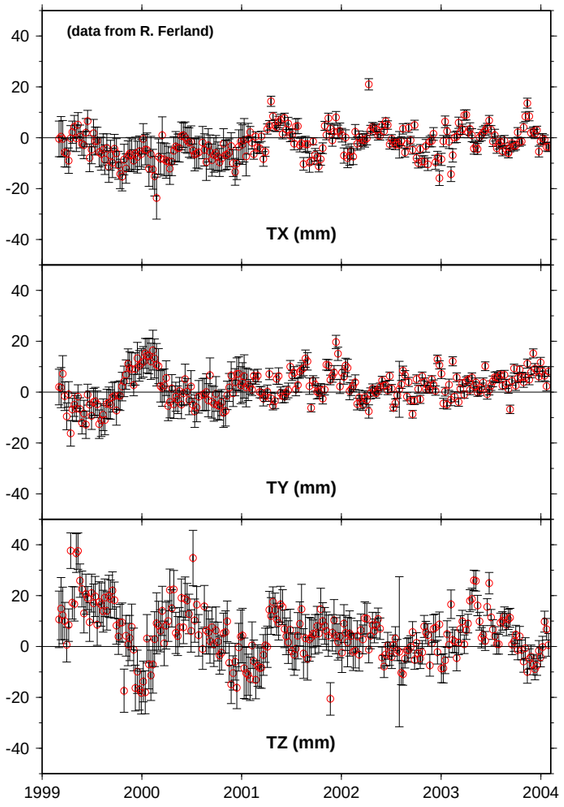
		Datum attributes (may be optimistic)		**Relative station coordinates**		
Short-term positioning daily (M. Heflin) weekly (R. Ferland)				N,E V N,E V	4 - 5 mm 10 mm 2 mm 6 - 7 mm	
IGS00 internal long-term precision (99 RF sites)	origin scale orientation	0.15 mm 0.74 mm 0.13 mm	0.15 mm/yr 0.36 mm/yr 0.12 mm/yr	N,E V	0.3 mm 0.5 mm	0.5 mm/yr 0.8 mm/yr
ITRF2000 long-term accuracy	origin (geocenter) equatorial axial scale orientation	 0.5 mm 0.9 mm 1.2 mm 0.6 mm	 0.1 mm/yr 0.3 mm/yr 0.2 mm/yr 2.0 mm/yr	3D	2 - 5 mm	0.5 - 2 mm/yr

Conventional Linear Framework

- **IGS00 & ITRF are globally stationary with linear internal evolution:**
  - **framework of points rigidly fixed to hypothetical solid Earth surface**
  - **points move only due to linear tectonic motions & known periodic tides**
  - **ITRF origin fixed at Earth's center of mass (CoM), including all fluids**
  - **origin realized by average of 5 long-term SLR solutions**
  - **no-net-global frame motions w.r.t. Earth's crust & CoM**

- **IERS Conventions 2003 specify this concept (with some inconsistencies)**

IGS Combined Geocenter



- **Does not recognize "geocenter motions"**
  - **centers of "instantaneous" satellite frames (weekly/monthly) appear to move w.r.t. CoM**
  - **net motion (few-mm level) presumably due to large-scale motions of Earth's fluid masses**
  - **however, technique noise is significant & agreement between techniques is poor**
  - **despite this, real geocenter motions probably significant at semidiurnal/diurnal/seasonal periods**
  - **geocenter motions should be associated with large-scale surface deformations due to loading**

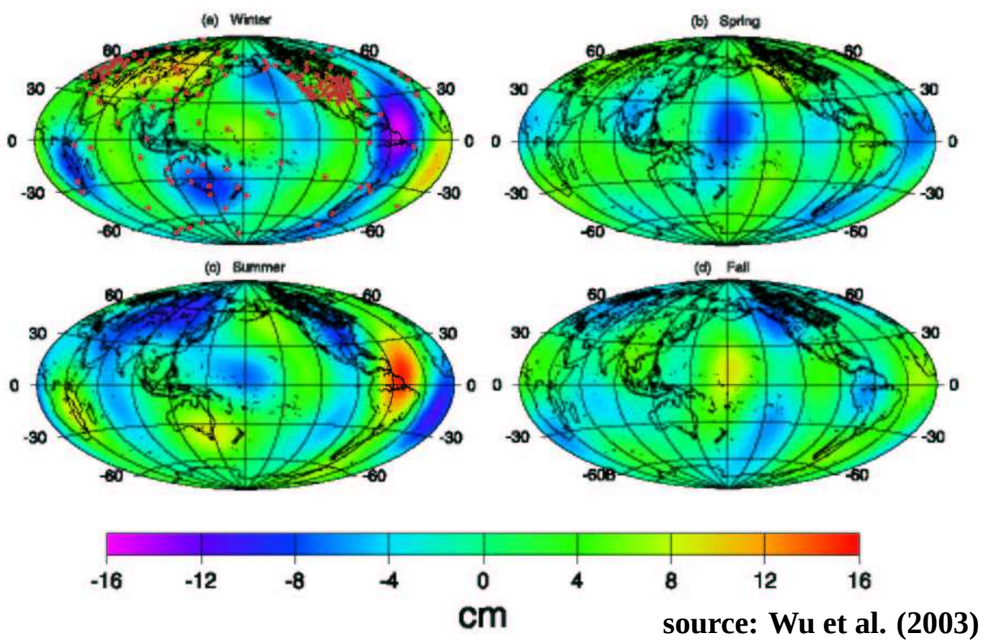
Handling Geocenter Motions

- **For geocenter motions, current ICRF $\Longleftrightarrow$ ITRF transformation can be elaborated:**

$$ICRF = P \times N \times R \times W \times [TRF(t) + O(t)]$$

  - **[TRF + O] is aligned to ITRF: vector O(t) from instantaneous TRF(t) center to ITRF origin**
  - **makes clear EOPs are expressed w.r.t. ITRF origin, not center of instantaneous TRF**

- **Can realize O(t) translations from Helmert transform between instantaneous TRF & ITRF**
  - **must simultaneously solve for rotation shifts & adjust EOPs consistently**
  - **requires uniform coverage of Earth surface for robust results**
  - **need fullest overlap of TRF & ITRF/IGS00 networks to minimize local/regional effects**
  - **also, ACs must handle station-related displacements similarly**



source: Wu et al. (2003)

- **Alternatively, could substitute degree 1 loading deformation terms in Helmert transform**
  - **would capture both geocenter motion & largest deformations**
  - **but to avoid aliasing requires degree & order 6 loading terms**
  - **thus dense network is also needed**

- **Recommend IGS approach using standard Helmert transform for IERS**

Conventional Station Displacements

- **IERS Conventions model for instantaneous station position is:**

$$X(t) = X_o + V_o \times (t - t_o) + \sum_i \Delta X_i(t)$$

  - **summation to include "high-frequency variations" given by "conventional models"**
  - **models given for solid Earth tides, ocean (tidal) loading, & pole tide**
  - **no models for atmospheric loading or geocenter motion**
  - **can account for tidal geocenter motion via ocean loading (not recommended by IERS)**

- **IERS Conventions not fully consistent or complete**
  - **ACs should handle model contributions the same way**
  - **otherwise, combined products will be uninterpretable**

- **Proposed interim "interpretation" for conventional displacements**
  - **most non-tidal geophysical effects should be left in geodetic parameters**
  - **include only those a priori models with accurate, closed-form expressions & with tidal periods (also add "permanent" solid Earth & pole tides)**
  - **IERS models OK for solid Earth tides, ocean (tidal) loading, & pole tide**
  - **still need models for diurnal/semidiurnal tidal atmospheric loading & geocenter motions due to oceans**

Analysis Improvements – Subdaily Variations

- **Aliasing problems**
  - **diurnal geophysical variations commensurate with GPS orbital period**
  - **unmodelled effects will alias partly into GPS orbits**
  - **diurnal/semidiurnal station errors alias into annual/semiannual signals (10 - 20%)**

- **Subdaily tidal EOPs**
  - **ACs should implement new IERS 2003 model – changes at few-mm level**
  - **8 terms $\longrightarrow$ 71 terms**
  - **peak differences: $\sim$100 μas & $\sim$12 μs ; RMS: $\sim$30 μas & $\sim$4 μs**
  - **model still needs improvement for S1 atmosphere effect**

- **High-frequency nutation in polar motion**
  - **IAU redefinition of nutation $\Rightarrow$ all effects with periods $<$2 d now polar motion**
  - **old prograde semidiurnal nutations (torques on triaxial Earth) now prograde diurnal PM**
  - **IERS 2003 gives 10 terms with amplitudes up to $\sim$15 μas**
  - **but no subroutine provided; should be included with subdaily EOPs**

- **Solid Earth tides**
  - **ACs should implement new IERS 2003 model – changes up to $\sim$2 mm vertical**
  - **subroutine available from Royal Observatory of Belgium (V. Dehant)**

Subdaily Variations (cont'd)

- **Subdaily geocenter motions**
  - **IERS 2003 recommendations inconsistent; no model provided**
  - **largest terms $\sim$5 mm in Z, 2 to 3 mm in X,Y**
  - **ACs should implement using ocean tidal loading model**
  - **model still needed to transform orbits to sp3 terrestrial frame**

- **Subdaily atmospheric pressure loading**
  - **IERS 2003 recommendations incomplete; no model provided**
  - **Special Bureau for Loading (van Dam et al., 2003) suggests:**

$$P(\phi, t) = P_{\max} \cos^3(\phi) \sin(t + 12^o)$$

  - $P_{\max} =$ **maximum loading amplitude at the equator**
  - **estimates for $P_{\max}$ are $\sim$0.8 mm for S1 & $\sim$1.5 mm for S2**

- **Note on non-tidal atmosphere pressure loading**
  - **including in GPS data analysis would be very cumbersome**
  - **far easier to handle in post-processing analysis**
  - **need to establish magnitude of errors if effect neglected**
  - **in any case, it is essential that all ACs handle effects alike**

Analysis Improvements – Other Effects

- **Pole tide**
  - **past IERS Conventions were unclear about mean reference pole**
  - **IERS 2003 provides two options – tabular file or linear fit**
  - **tabulated mean pole file ended in 2000**
  - **ACs should implement linear trend for mean pole position**

- **Nutation model errors**
  - **satellite tracking highly insensitive to celestial pole offsets**
  - **however, nutation-rate errors can alias into GPS polar motion results**
  - **IAU1980 error at 13.66 d causes PM-rate error of $\sim$70 $\mu as/d$**
  - **equivalent to fortnightly PM error of $\sim$150 μas**
  - **ACs should not rely on IAU1980 without applying daily nutation corrections from IERS**

- **Neglected ionospheric corrections**
  - **neglect of 2nd order effect ($\propto \mathrm{B/f^3}$) causes few-mm latitude errors**
  - **mainly diurnal, semiannual & decadal variations; largest near equator**
  - **more by S. Kedar, G. Hajj, M. Heflin, & B. Wilson this session**

IGS Combination Procedures

- **Step 0. AC weekly solutions for TRF, ERPs, orbits, clocks, tropos**
  - **must be internally self-consistent & unconstrained**
  - **reference frame free (or minimally constrained)**
  - **sampling: 1 week/TRF; 1 d/ERPs; 15 min/orbits; 5 min/clocks; 2 hr/ZPD**
  - **provide full variance-covariance for TRF + ERPs in SINEX format**

- **Step 1. SINEX files combined for weekly frames & daily ERPs**
  - **inputs deconstrained, checked, reweighted & Helmert aligned to IGS00**
  - **apparent geocenter offsets removed; scales changed to IGS00 (0 to +2 ppb)**
  - **IGS combined TRF formed from inputs by weighted least-squares**
  - **weekly terrestrial frame has IGS00 origin & scale**

- **Step 2. Orbits & clocks combined**
  - **AC rotational offsets from SINEX combination applied to orbits**
  - **no translational or scale offsets applied**
  - **AC weighting independent of SINEX combination**
  - **orbits & clocks consistent with original center-of-mass frame (not weekly TRF)**

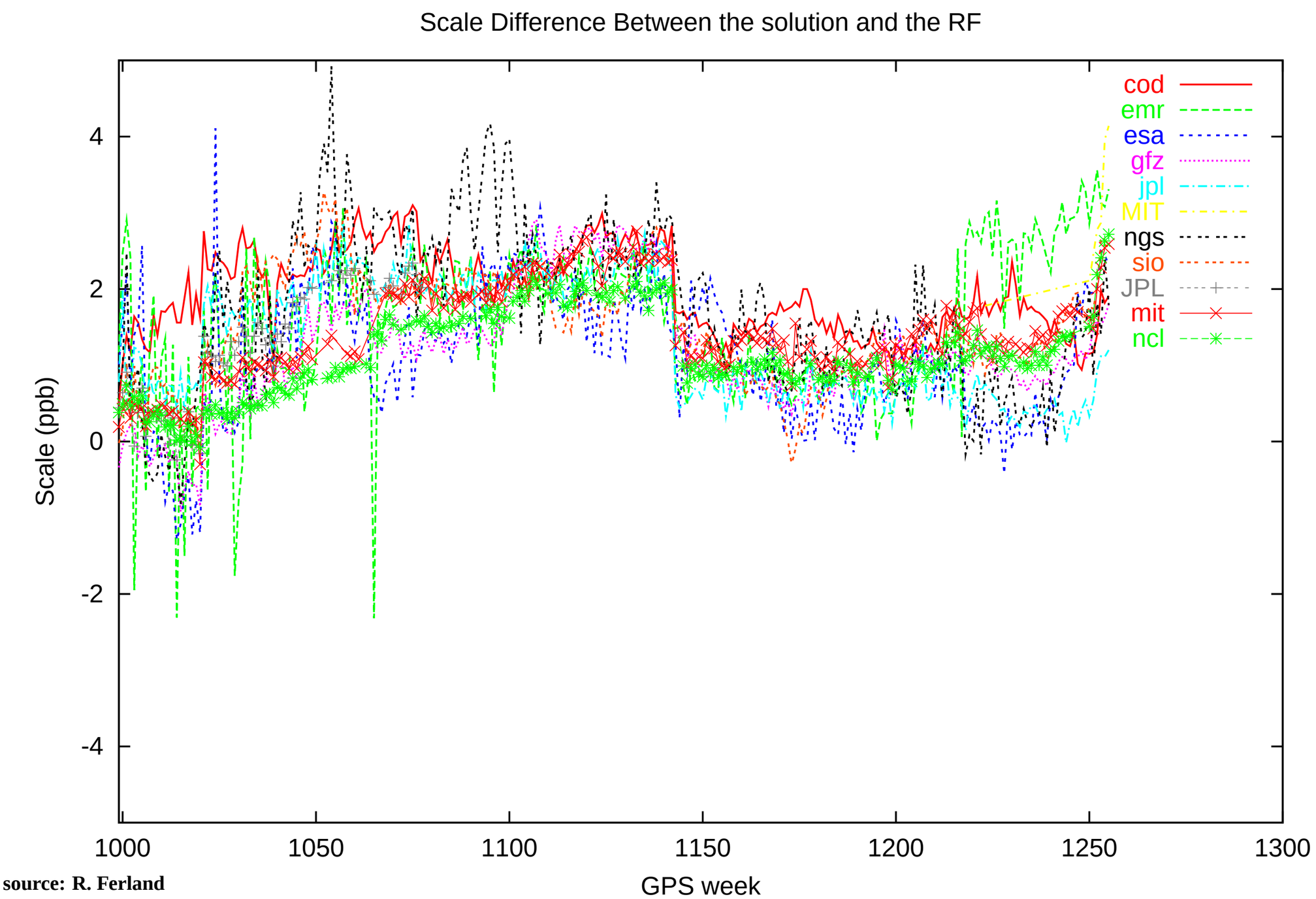
IGS Combination (cont'd)

- **Step 3. Tropo & iono combinations**
  - ionospheric maps not sensitive to IGS frame (except via clock & satellite biases)
  - tropo ZPDs should account for shifts in station position & scale
  - effect of station position differences very minor
  - effect of scale difference may not be negligible

- **Separate processing: Rapid & Ultra-rapid products**
  - ACs use IGS00 reference stations fixed
  - orbits, ERPs, clocks & ZPD, but no TRF solution
  - product frames are nominally IGS00
  - but orbit dynamics still respond to center-of-mass, so actual frame ambiguous

- **Planned changes – "absolute" antenna patterns for satellites & stations**
  - by design, will enforce IGS00 scale on all IGS products
  - could eliminate current scale inconsistencies among products
  - but GPS solution for satellite antennas must match mean scale of AC solutions

Scale Differences among IGS AC Frames



source: R. Ferland

Nominal Reference Frames of IGS Products

Product set	Origin	Scale
Finals:		
terrestrial frame (SINEX)	IGS00 (shifted)	VLBI/SLR via ITRF2000 & IGS00
orbits	center-of-mass[a]	GPS (AC average)[b]
clocks	center-of-mass[a]	GPS (AC average)[b]
troposphere	ambiguous (insignificant)	GPS (AC average)[b]
Rapids & Ultra-rapids:		
all	IGS00[c]	VLBI/SLR via ITRF2000 & IGS00[c]

[a] differs by weekly geocenter offset from IGS00

[b] all scales should shift to IGS00 when “absolute” antenna phase patterns are adopted

[c] Rapid/Ultra-rapid frames respond partially to orbital dynamics & center-of-mass origin

Summary of IGS Product Inconsistencies

Usage	Inconsistency	Remedy
PPP – fixed IGS Final orbits & clocks	origin offset from weekly SINEX frame;	apply weekly IGS geocenter offsets (approximate only);
	scale different from weekly SINEX frame[a]	none currently available[a]
double-differenced global network – fixed IGS Final orbits	origin offset from weekly SINEX frame	apply weekly IGS geocenter offsets (approximate only)
long-term global network – fixed IGS Final orbits	sp3 files aligned to different IGS frames	transform with trnfsp3n & adjust rot/trans offsets
tropospheric path delays	origin & scale[a] not precisely defined	none currently available[a] (origin not significant)

[a] scales inconsistencies should vanish when “absolute” antenna phase patterns are adopted

Improvements in Future ITRF Realizations

- **Ongoing improvements in all contributing techniques**
  - **longer observing histories**
  - **technique & modeling enhancements**

- **Time series combination of TRF + EOPs**
  - **allows temporal variations in station positions to be handled better**
  - **yields EOP time series consistent with ITRF**
  - **can identify outliers & other problems**

- **New geophysical models being developed for no-net-rotation condition**
  - **more global coverage of Earth's surface & use of space geodetic results**
  - **more sophisticated approaches using finite element modeling, etc**
  - **should give improved rotational stability**

- **Colocation & local tie problems remain**
  - **need more colocation sites & better distribution**
  - **errors in local tie remain a major limitation**

Improved IGS Reference Frame Realizations

- **Develop long-range, proactive strategy**
  - **long-term stability requires long view**
  - **must take active posture to promote & achieve optimal frame**
  - **should not accept only what is currently available**

- **Designate “official” reference frame stations**
  - **drop meaningless “global” station label**
  - **develop mutually acceptable operating standards**
  - **solicit commitments for long-term operation from stations**
  - **strictly enforce specifications**
  - **try to improve global coverage of network**

- **Develop quality assessment & monitoring system**
  - **problems at reference stations must be quickly identified & fixed**

- **Improve user interfaces**
  - **delivery of reference frame to users needs to be greatly simplified**
  - **automated, certified PPP service recommended**

Summary of Recommendations

1. Develop reinforced, long-range IGS reference frame strategy

2. Verify IGS PPP product consistency

3. Provide IGS PPP service to users

4. Verify IGS scale consistency using absolute antenna patterns

5. IERS should adopt IGS approach for geocenter motions

6. Interpretation for conventional station displacement models

7. Ensure consistency of IGS troposphere products

8. ACs implement consistent subdaily analysis models

9. ACs implement linear mean pole for pole tide

10. ACs do not rely on uncorrected IAU1980 nutation model

11. Consider adding 2nd order ionosphere correction