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"Error Budget"

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Subject: Error budget - draft
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1. Motivation

1. We have scatter in our results that is larger than we can account for. The sources of this excess scatter need to be understood in order to get rid of the sources of error or to include the uncertainties properly.
2. In addition to daily and longer time scales (e.g., for site position or baseline length values and rates of change) we should begin to look to the future when we will put out sub-daily results, so we have to have uncertainties to go with estimates, e.g. uncertainties of 2 hour estimates of UT1, ZWD, or ZTD.
3. The accurate assignment of uncertainties is important for interpretation of geophysical modeling and for combination of results among the space geodetic techniques. In principle the relative weighting for combination should be determined by the properly determined accuracies of each technique.

2. Preliminaries

The level of detail and quantification proposed in this memo are goals that should be kept in mind. However, not all effects can be modeled with the same accuracy, nor can the additional information provided by the inclusion of correlations, either among parameters at a given time, or for a parameter over a span of time, be easily included. The objectives of this memo are to begin the process of improving the way errors are modeled and to improve the accuracy of the uncertainties. Before trying to lay out the list of "error sources", it will be useful to come to some agreement on what should go into an "error budget". Although the result of any measurement has "errors", we can only provide the "uncertainty" of the measurement or parameter estimate. Unfortunately, the two words are used interchangeably, and our efforts to derive the best estimates of the uncertainties in our geodetic parameters are likely to continue that practice.

While the intent of this memo is to outline the process for arriving at an error budget, the subsequent reports will provide the models and/or values for filling it out. In addition to defining the model or error source under study, an effort should be made to define the time scale for which the uncertainties related to that model or source of error are applicable. This additional information is of increasing importance as the time interval of reported results is expanded to smaller values.

3. Terminology

1. What is an "error' (uncertainty)?
   i. uncertainty due to a measured parameter (e.g. uncertainty in measured height of antenna assumed due to thermal deformation)
   ii. uncertainty due to a modeled parameter (e.g. uncertainty in inferred height change due to uncertainty in temperature and relation of temperature to height)
   iii. incorrectly modeled process, e.g., using piecewise linear function as model for continuously varying atmosphere delays and clocks
2. How can error quantification be evaluated?

   Need to look at evaluation both of total modeled uncertainty (does scatter agree with accountable error sources) and of changes in a model (i.e. is a new model significantly better than a previous model, based on the accountable error for each model?)

3. What VLBI parameter(s) should be used for evaluation?
   i. R_L (baseline length repeatability or change in baseline length repeatability)
   ii. repeatability of site position (WRMS of East/North/Up)
   iii. other?

4. **Classifications**
   1. instrumental vs geophysical
   2. baseline vs station
   3. harmonic vs stochastic

5. **Evaluation**

   Is χ^2/degree of freedom equal 1 using known error sources?

   Evaluate for times, T_i, up to (for example):

   scan length (~1 min)
   15 min
   3 hours
   24 hours
   1 week
   2 months
   1 year
   10 years

   Don't forget weak stations (scan time may be longer)!

6. **Process for evaluating accuracy of models for uncertainties (ideal)**
   1. Quantify error/uncertainty for
      i. the effect (e.g., antenna SEFD, atmosphere pressure loading, etc)
      ii. is it a station or a baseline effect?
      iii. what are the uncertainties at different time scales, T_i (e.g., 1 minute, 20 minutes, diurnal, annual, etc)
      iv. What are **phases** for errors in un-modeled or incorrectly-modeled harmonic effects, e.g. annual components of hydrology and thermal deformations
   2. Quantify correlations (e.g., diurnal temperature and pressure changes are correlated and both affect vertical component of position through antenna structure deformation and atmospheric pressure loading)
   3. Include errors/uncertainties (covariance) in estimation for appropriate parameters
      i. within a session (daily and shorter)
      ii. across multiple sessions *(no way to do this now!)*)
   4. Evaluate at the T_i
   5. Was something missed or evaluated incorrectly?
   6. Back to 1

7. **Group delay error sources (should we also include phase delay?); how much detail?**
   (This is obviously not complete, but perhaps enough items are listed to illustrate the range of parameters that needs to be included if we are to develop a good model.

   1. System delay error per scan (baseline effect, but enters by site)
      T_i = scan: T_{sys}, antenna diameter, efficiency, frequency sequence, scan length, correlated flux density of radio source, ?

Does SNR from *fourfit* match expected value from system parameters?

2. Instrumental delay errors
   i. Uncorrected cable delay
      T_i = hours
   ii. Cross polarization
      T_i = scan
3. Frequency standard (probably global parameter for foreseeable future, unless we find some way to evaluate for individual sites)
   T_i = scan: reasonably working H-maser not a limit here (10^{-12}/T seconds out to > 10^3 sec contributes only 1 psec noise)
   $T_i > 10^3$ sec: need to include correlation with atmosphere uncertainty
   What unmodeled error is introduced by treating clock as piece-wise linear with constraints rather than as continuously varying?
4. Atmosphere error (treat separately azimuthally symmetric and non-symmetric (now modeled usually as spatial gradient))
   T_i = scan ($T \leq$ few minutes): determined by turbulence model; function of elevation; different by site and time of year
   T_i = 1h – 6h: mapping functions
   T_i = days: mapping functions
   What unmodeled error is introduced by treating atmosphere delay as piece-wise linear with constraints rather than as continuously varying?
   What is the uncertainty in the calculation of delay-variance per unit time from delay rates (as used in *solvk* Kalman filter estimation), and how does it propagate to delay error?
   What are correlation times? i.e. mapping function errors are correlated over hours, at least.
5. Antenna structure deformation - thermal
   i. Measured height/horizontal:
      uncertainty: measurement uncertainty at all time scales
   ii. Calculated height/horizontal change based on temperature:
      include error in measured temperature as propagated through model, e.g., uncertainties in thermal expansion coefficients, time lag, error due to location of temperature sensor and mapping to effective point on antenna.
         T_i = 1h – 6h, depends on time lag uncertainty; corrections correlated over this time.
6. Antenna structure deformation - gravitational
      what is uncertainty in deformation? function of elevation? hour angle/dec?
7. Radio source structure
   i. Structure phase
      T_i = scan:
         vector baseline and frequency dependent
   ii. time-dependent position:
      T_i = days to years:
         frequency dependent
         what is uncertainty if a structure phase correction is made within a session?
8. Ocean loading (applies to other loading effects also)
      uncertainty in response
      uncertainty in driver