Outline of Level 2 Measurement Requirements and Error Budgets Down to Level 3 GNSS-RO Instrument, Mission, Ground, and GNSS Constellation Requirements

In support of the CLARREO Pre-Phase A mission study, CLARREO project personnel are conducting concept studies related to the Global Navigation Satellite System – Radio Occultation (GNSS-RO) instrument. Studies include efforts to develop a flow down, including error budgets, from measurement requirements to instrument requirements.

The radio occultation instrument of CLARREO is intended to capture a snapshot of the state of the atmosphere with uncertainty in that state, determined empirically, that can be used to accurately determine change on decadal timescales. By comparing a retrieved quantity derived from well calibrated, reproducible observations from one epoch to the next using a common retrieval algorithm, the change of the atmosphere as revealed in a retrieved quantity is determined without contribution from retrieval error. Consequently, retrieval error is irrelevant to CLARREO radio occultation. On the other hand, all errors that directly affect the observation of the SI-traceable observation are relevant; these are "individual sounding" errors. Moreover, because CLARREO seeks accurate snapshots of the state of the global atmosphere, errors due to sub-sampling in space and time are also relevant; these are "climatological averaging" errors.

Both the individual sounding errors and the climatological averaging errors contain contributions that are random and some that are potentially systematic. The many sources of error that are random can be reduced by averaging increased numbers of soundings together. Those that are systematic cannot be reduced by increased averaging. For CLARREO, the two types of error must be considered separately because they lead to different instrument and mission requirements. What follows is an extensive but not yet complete list of sources of error, categorized by individual sounding vs. climatological averaging and further by random vs. systematic.

I. Measurement Requirement A: Individual Sounding
   A. Systematic Error:
      1. Retrieval Non-Linearity
         (a) Provide sufficient signal-to-noise ratio (SNR) to suppress any systematic error that may arise in the retrieval of refractivity.
      2. RO Occultation Link
         (a) Antenna phase center determination (pre-launch activity)
      3. Atmospheric multi-path
         (a) Provide sampling rate that eliminates this vertical coverage error
      4. Ionospheric Calibration
         (a) Provide data that allows for science data processing to perform ionospheric calibration, i.e., remove ionospheric contribution to occultation to first order. This implies the need to provide data that tracks two well spaced carrier frequencies of the occulted transmitter from 0-50km.
         (b) Provide data that permits bracketing of residual influence of ionosphere on phase delay and that potentially allows for significant elimination of

residual influence of the ionosphere. Implies tracking of at least one additional frequency in the occultation link.

5. CLARREO LEO orbit knowledge (Precise Orbit Determination)
   (a) Position Error – Considered to be negligible relative to Velocity Error considerations
   (b) Velocity Error <XX mm/sec
6. Clock Accuracy (10^{-XX} over 1 second, or XX mm/s), to be achieved on all of the following system components
   (i) Receiver clock
   (ii) GNSS transmitter clocks
   (iii) Ground station clocks
7. Mission Requirement on Attitude knowledge: must know position of occultation and POD antenna phase centers with respect to Observatory center of mass.
8. Mission Requirement on Attitude Rate knowledge: must know position of occultation and POD antenna phase centers with respect to Observatory center of mass.
9. Mission Requirement on local multi-path: must assure that potential reflections of GPS signals off of the spacecraft are minimized by geometry and antenna gain patterns.

B. Random Error:
   1. Instrument Precision (will have a budget that will drive design)
   2. Ionospheric Scintillation (will have a budget that doesn't drive design)
   3. Gravity Waves (will have a budget that doesn't drive design)
   4. Clock Precision

II. Measurement Requirement B: Climatological Averaging
   A. Systematic Error:
      1. Sampling the diurnal cycle
         (a) Mission requirement on number of CLARREO satellites, their longitudes of ascending node, and their precession rates (regression of nodes).
      2. Retrieve Refractivity over 0-50km
         (a) This implies the need for sufficient SNR to provide for retrieving from 0-50km.

   B. Random Error:
      1. Sampling Density
         (a) Mission requirement on number of CLARREO satellites and their inclinations.
         (b) Instrument requirements on number of GNSS constellations tracked
         (c) Instrument requirements on number of occultation antennas (fore and/or aft)

The following table contains notional/preliminary error budgets, which are representative of the troposphere. Verification will ultimately be performed for distinct altitude levels. Supporting rationale will eventually be provided that demonstrates that verification at these distinct altitude levels is sufficient to assure requirements are met over the required altitude ranges.

	Troposphere (5-20km)		Lower Troposphere (2-5km)	
	Testing that requirements are met for this region to be done at 18km.		Testing that requirements are met for this region to be done at 3km.	
	Phase rate error (mm/s)	**Refractivity error (%)**	**Phase rate error (mm/s)**	**Refractivity error (%)**
Measurement Requirement A: Individual Sounding				
Systematic				
Retrieval Non-Linearity	0.000	0.0000%	0.150	0.0050%
RO antenna phase center determination	0.021	0.0007%	0.021	0.0007%
Atmospheric multipath	0.000	0.0000%	0.000	0.0000%
Ionospheric residual	0.300	0.0100%	0.060	0.0020%
LEO POD	0.054	0.0018%	0.000	0.0000%
Clock accuracy	0.030	0.0010%	0.000	0.0000%
Attitude knowledge	0.024	0.0008%	0.024	0.0008%
Attitude rate knowledge	0.150	0.0050%	0.030	0.0010%
Local multi-path	0.240	0.0080%	0.060	0.0020%
Total	0.418	0.0139%	0.178	0.0059%
Random				
Instrument precision	0.240	0.0080%	0.060	0.0020%
Ionospheric scintillation	0.060	0.0020%	0.000	0.0000%
Gravity waves	0.090	0.0030%	0.000	0.0000%
Clock precision	0.099	0.0033%	0.000	0.0000%
Total	0.281	0.0094%	0.060	0.0020%
Measurement Requirement B: Climatological Averaging				
Systematic				
Diurnal cycle	n/a	0.0100%	n/a	0.0300%
Insufficient SNR to Retrieve	n/a	0.0020%	n/a	0.0500%
Total	n/a	0.0102%	n/a	0.0583%
Random				
Sampling density	n/a	0.0220%	n/a	0.0800%
Total	n/a	0.0220%	n/a	0.0800%
Total systematic error (target)		*0.0170%*		*0.0570%*
Total systematic error		**0.0173%**		**0.0586%**
Total random error (target)		*0.0250%*		*0.0820%*
Total random error		**0.0239%**		**0.0800%**