Hardware Delays at the ATF/OSF (B. Vila-Vilaro,NAOJ)

I was unable to attend the first Telcon on this matter, so I have relied somewhat on the notes of the meeting that have been distributed around.

If my understanding is correct, the main issue we are facing right now is the real possibility that some of the critical hardware (i.e., nutators, amplitude calibration devices and pFE) will be delivered at the ATF later than expected.

This obviously raises the issue of how to take maximum advantage of whatever is available at any point in time at the ATF, and what testing/measurements will have to be deferred to the AOS.

I hope we are all in the same page on this, but let me first point out the following issue:

"Testing" vs. "Measuring":

There is a big difference between "testing" an observing mode and getting some useful data out it. For instance, the act of mapping a planet will test a lot of antenna, RX control issues and offline software tools, but does NOT need to be done in good weather, etc if there is NO specific actual measurement involved in the process (just taking data for the sake of it, basically). For most TP "measurements" I can think of (except pointing), some sort of calibration will be required, which implies that we will NEED a calibration device at the time. For e2e "testing" or pointing, we will NOT need a calibration device, but still will require a fairly extensive software tooling (weather data + atmospheric models for refraction corrections, etc, etc).

In the following, I will use "testing" and "measuring" as described here.

What TP Modes Do We Actually Need?

So the initial problem can be rephrased into, what TP modes do we actually want to "test" and/or "measure" at the ATF/OSF?.

This can be answered by stating WHAT TP modes will be required by the AIV/CSV Team in Chile and then backtracking in time/site to see where can they actually be tested.

My (somewhat) personal view is that we should have, at least, the following TP capabilities for adequate AIV/(early)CSV:

-Being able to point (OPT and Radiometric)

-Being able to Focus the Subreflector
-Being able to take Beam maps and measure beam efficiencies
-Being able to Calibrate using the Relative Amplitude Calibration Devices
-Being able to carry out Single-Dish Polarization Observations
-Being able to take Sky Dips

Based on this list, I have explored what can be done at each site in the event that some of the hardware is late.

<u>In the event of delays in Nutators:</u>
There are several TP modes required by ALMA that DO NOT use a nutator, so they can be "tested" and used for "measurements" at both sites:

1. <u>Total Power Modes that do NOT require a nutator:</u>
1) OTF with fixed subreflector
2) Frequency Switching Modes
3) Position Switching Modes
4) Sky Tips
5) Amplitude Calibration
6) Single-Dish Polarization Observations (some cases)

Here is a brief summary of the Requirements:

Mode	Spectral/Continuum	Amp Cal Dev & Atm Data	Notes
Fast OTF	BOTH	Desirable	Fast Antenna Scanning Capabilities Required
Freq SW	Spectral	Desirable	FLOOG Capabilities
Pos SW	BOTH	Desirable	
Sky Tips	Continuum	Required	Amplitude Cal Dev Required
Amplitude Cal	Spectral Continuum (Tests)	Required	ATM & atm data required
Single-Dish Polarization	BOTH	Desirable	Polarization Standard Catalogues?

For "testing" of any of this modes, calibration is not absolutely necessary. However, if any kind of "measurement" is intended, an amplitude calibration device will be required. Furthermore, all modes will require, at least, offline data reduction capabilities (irrespective of the data being calibrated or not) and it would be desirable to have some online display tools. Obviously, for the spectral modes, a spectral backend has to be available.

2. The weather factor (Sensitivity):

The first issue is to consider how sensitive an observation can be carried out at either site. This calculation is usually done assuming only the average properties of the atmosphere (bulk transmission). Variations of these properties within the timescales of the measurements are dealt with in the next section.

a) The ATF

Using the data in the MMA Memo 237 by B. Butler and the ATM atmospheric model, I get the following monthly mean optical depths at 90GHz and 225GHz (at the zenith):

Period	PWV(mm)	τ(90GHz)	τ(225GHz)
December-April	5	0.05	0.233
May, October	7	0.06	0.353
June	9	0.08	0.491
July-September	10-15	0.09-0.14	0.568-1.023

The optical depth at the CO(1-0) line would be a factor ~4 of that at 90GHz. This can be easily translated to system temperatures at any elevation using the current antenna and RX specifications. I list here the expected values for winter months and monsoon weather season for reference:

Winter Months:

ELV(deg)	Tsys(90GHz)(K)	Tsys(115GHz)(K)	Tsys(225GHz)(K)
80	84.5	147.3	162.5
60	86.2	158.9	176.6
45	89.9	181.9	204.9
20	117.4	348.6	414.5

Monsoon Season:

ELV(deg)	Tsys(90GHz)(K)	Tsys(115GHz)(K)	Tsys(225GHz)(K)
80	110.5	281.7	517.2

60	116.1	319.1	611.6
45	127.4	395.9	819.1
20	205.3	1089.9	3416.5

Using the Aperture efficiency values (including RX) listed in Sugimoto (2005) for the ALMA 12m antennas, I get the following continuum sensitivity for a 2GHz bandwidth and 1 sec integrations (33.7Jy/K @ 90GHz, 31.8Jy/K @115GHz and 33.7Jy/K @225GHz):

Winter Months:

ELV(deg)	Sens(90GHz)(Jy)	Sens(115GHz)(Jy)	Sens(225GHz)(Jy)
80	0.0637	0.105	0.122
60	0.0651	0.113	0.133
45	0.0678	0.129	0.154
20	0.0885	0.248	0.312

Monsoon Season:

ELV(deg)	Sens(90GHz)(Jy)	Sens(115GHz)(Jy)	Sens(225GHz)(Jy)
80	0.0833	0.200	0.389
60	0.0875	0.227	0.461
45	0.0960	0.281	0.617
20	0.155	0.775	2.575

For a purely switched observation, the above tables need to be multiplied by a sqrt(2); for Fast OTF the numbers should be OK.

For spectral modes the sensitivity will depend on the frequency resolution being used. Given that most of the possible galactic targets would have linewidths of a few tens of km/s (at most), resolutions between 0.5-1MHz will be needed. This is a factor 40-60 worse sensitivity than in the continuum case for the same integration time. Spectral-line observations have, though, the advantage of being able to fit baselines that counter somewhat the effects of short-timescale atmospheric transparency variations.

b) The OSF:

It is a bit trickier to estimate this since there are no measurements of opacity at the OSF right now. I have used instead the yearly average data of the SMTO(HHT) telescope site in Arizona (USA), because of similar height of the site and surrounding environment. As soon as possible we should start gathering data on the OSF properties, though.

I made an average of the optical depths for different PWV levels for the months straddling the monsoon season in Arizona, which would be equivalent to the Bolivian winter (I am assuming that we will not be able to do much observing during that period at the OSF either). Averaging the whole data sets for the period 1993 to 2005, I get the following time percentages of PVW better than the listed number (or equivalent 225GHz opacity) and opacity values at the centers of several ALMA Bands (Zenith Values):

PWV/τ	Time Percentage	τ 90GHz	τ 225GHz	τ 345GHz	τ 460GHz
PVW≤5.7mm τ(225) ≤0.30	71%	0.05	0.30	1.02	4.68
PVW≤2.85mm τ(225) ≤0.15	40%	0.03	0.15	0.50	2.33
PVW≤1.4mm τ(225) ≤0.075	12%	0.02	0.08	0.26	1.15
PVW≤1.1mm τ(225) ≤0.060	7%	0.02	0.06	0.21	0.92

Going to higher frequencies than that is pretty pointless from the statistics (there is a factor ~20 higher opacity than at 225GHz for any frequency above 490GHz). As it should be expected, the OSF will be a better site than the ATF most of the time. Also, we should expect to have a fairly significant Band 7 weather window there (say ~40% of the observable time on average). I do not think it is worth trying anything above that frequency, though. Assuming that OSF "measuring" will be carried out under the top two row conditions, the corresponding Tsys and continuum sensitivity Tables are:

71% Weather Conditions:

ELV(deg)	Tsys(90GHz)(K)	Tsys(225GHz)(K)	Tsys(345GHz)(K)
80	85.1	277.3	1201.9
60	86.8	301.3	1431.4
45	90.7	349.4	1957.7
20	119.2	724.6	10265.1

ELV(deg)	Sens(90GHz)(Jy)	Sens(225GHz)(Jy)	Sens(345GHz)(Jy)

80	0.064	0.209	1.056
60	0.065	0.227	1.258
45	0.068	0.263	1.720
20	0.089	0.546	9.021

40% Weather Conditions

ELV(deg)	Tsys(90GHz)(K)	Tsys(225GHz)(K)	Tsys(345GHz)(K)
80	77.1	194.5	582.3
60	77.8	204.2	645.6
45	79.5	223.2	776.6
20	94.6	355.9	1999.2

ELV(deg)	Sens(90GHz)(Jy)	Sens(225GHz)(Jy)	Sens(345GHz)(Jy)
80	0.058	0.146	0.512
60	0.059	0.154	0.567
45	0.060	0.168	0.682
20	0.071	0.268	1.757

The same factors as in the ATF case apply for purely switched and OTF observations.

3. <u>The Weather and RX Factor (Stability):</u>

Since nutators can switch quickly between relatively nearby sky positions, they are usually quite efficient in getting rid not only of the emission of the bulk of the atmosphere, but also of the short timescale fluctuations in the opacity along the line of sight (due to fluctuations in the atmospheric properties, PWV content, etc). Nutators will NOT, however, get rid of the 1/f noise from the RX system (this should only be a problem for system-dominated observations at low frequencies and slow chopping).
In the event that we want to “measure” antenna properties without a nutator, we will have to use modes that can mimic the nutators as much as possible.

Most mm and sub-mm single-dish observatories on intermediate altitude sites report the presence of atmospheric regimes of low opacity and high instability. For the ALMA site, this can be readily explained by the lack of correlation between the opacity and the EPL (as measured by the site testing interferometers). It should be expected that we will experience the same kind

of problem at both sites. Without extensive site testing I cannot thus estimate the degree of correlation of these at either site, and will have to assume probabilities here.
I derive the opacity fluctuations along the line of sight by using the following relationship between opacity and EPL fluctuations:

$$\delta\tau \approx \frac{\delta\tau}{\delta w}\frac{\delta w}{\delta L}\delta L \approx \xi\delta L$$ where w is the PWV and L is the EPL

Using the ATM model, I get the following values for ξ:

Freq(GHz)	ξ(1/mm)
90	0.0012
225	0.0089
345	0.0275

Making the usual assumptions (phase screen in a frozen flow regime with an average velocity of 10m/s passing over the observatory and that the structure function increases with distance as the sqrt of the zenithal distance, same ON-OFF times) and using the phase structure functions, the worst-case-scenario approach EPL fluctuations (highest possible fluctuations for a referenced ON-OFF observation in AZ) will go as:

$$\sigma_L \approx \frac{\lambda}{2\pi}\sqrt{D_\phi(\rho)}$$

$$\rho \approx (t_{ON}/2 + t_{slew})v_{sc} + d_{OFF}$$

$$d_{OFF} \approx H\tan\theta$$

where D is the structure function of the phase fluctuations, λ the observing wavelength, t(ON) the ON time, d(OFF) the projected distance on the phase screen of the OFF w.r.t the ON positions, H the height of the phase screen (~1km), θ the angular separation of ON and OFF, t(SLEW) the slew time between ON and OFF and v(scr) the velocity of the phase screen. I set the slew time to 1sec (in reality may be longer).

For the EPL at the ATF I have used the data from the API test interferometer at the VLA site. The phase fluctuations under median weather conditions I get are (clear day-night effect):

EPL σ(11.3GHz), 300m	Day	Night
Summer Months	536μm	357μm
Rest of Year	346μm	223μm

Since the median phased fluctuations at the AOS with a very similar site testing interferometer give EPL of ~190μm, it appears that we will not be able to reduce the sky opacity fluctuations at the OSF much below the nighttime fluctuations for non-summer months at the ATF (only ~10% better).

Using the above parameters, I get the following sky brightness fluctuations (in Jy) at the ATF for 1sec, 5sec, 10sec and 20sec ON source time cycles, 1arcmin REF angular separations, and several elevations (S(D)=Summer, Daytime; S(N)=Summer,Nighttime; W(D)=Rest of Year, Daytime; W(N)=Rest of Year, Nighttime):

90GHzFluct(Jy),1arcmin	1sec				5sec			
ELV(Deg)	S(D)	S(N)	W(D)	W(N)	S(D)	S(N)	W(D)	W(N)
80	0.53	0.36	0.36	0.23	1.04	0.69	0.71	0.46
60	0.56	0.37	0.38	0.25	1.10	0.73	0.75	0.48
45	0.60	0.40	0.41	0.27	1.18	0.78	0.82	0.53
20	0.74	0.49	0.55	0.35	1.44	0.96	1.07	0.69

90GHzFluct(Jy),1arcmin	10sec				20sec			
ELV(Deg)	S(D)	S(N)	W(D)	W(N)	S(D)	S(N)	W(D)	W(N)
80	1.60	1.07	1.09	0.70	2.59	1.73	1.76	1.14
60	1.68	1.12	1.15	0.74	2.73	1.82	1.86	1.20
45	1.81	1.21	1.25	0.81	2.93	1.95	2.03	1.31
20	2.20	1.47	1.64	1.06	3.57	2.38	2.67	1.72

225GHzFluct(Jy), 1arcmin	1sec				5sec			
ELV(Deg)	S(D)	S(N)	W(D)	W(N)	S(D)	S(N)	W(D)	W(N)
80	1.98	1.32	2.12	1.37	3.86	2.57	4.15	2.67
60	1.89	1.26	2.17	1.40	3.68	2.45	4.25	2.74
45	1.67	1.13	2.23	1.44	3.31	2.21	4.36	2.81
20	0.74	0.49	2.06	1.33	1.44	0.96	4.02	2.59

225GHzFluct(Jy), 1arcmin	10sec				20sec			
ELV(Deg)	S(D)	S(N)	W(D)	W(N)	S(D)	S(N)	W(D)	W(N)
80	5.93	3.95	6.36	4.10	9.61	6.40	10.32	6.65
60	5.65	3.76	6.52	4.20	9.17	6.11	10.57	6.81
45	5.09	3.39	6.68	4.31	8.26	5.50	10.84	6.99
20	2.21	1.47	6.18	3.98	3.58	2.38	10.02	6.46

The same calculation for median conditions at the OSF give:

90GHz Fl(Jy) 1arcmin	1sec	5sec	10sec	20sec
ELV(deg)				
80	0.20	0.39	0.60	0.97
60	0.21	0.41	0.63	1.02
45	0.23	0.45	0.69	1.12
20	0.31	0.61	0.94	1.52

225GHz Fl(Jy) 1arcmin	1sec	5sec	10sec	20sec
ELV(deg)				
80	1.25	2.45	3.76	6.10
60	1.30	2.54	3.90	6.32
45	1.37	2.67	4.10	6.65
20	1.45	2.84	4.36	7.07

These tables show that:

-The OSF has less atmospheric fluctuations than the ATF (no surprise here). The average is lower than even the best nightly averages at the ATF.

-The atmospheric fluctuations are larger (by at least an order of magnitude!) than the thermal noise for the current ALMA RXs. The nutators would eventually revert this trend since for shorter integration times, the thermal noise will raise while the atmospheric fluctuations will decrease significantly.

What is left is to estimate the 1/f noise from the RX system and compare it with these numbers.

Assuming that the noise from the RX system behaves as 1/f up to, at least, a few tens of seconds, the 1/f noise will go as:

$$\delta S_{flick} \approx \alpha T_{sys} \frac{\delta G}{G}$$

where α is the conversion factor from antenna temperatures to flux units and dG/G~3e-3 (current ALMA RX specification). Please note that the flicker noise does NOT depend on the integration times. Using the values for Tsys listed above, this results in the followinf flicker noise levels at the ATF:

Flicker Noise (Jy)	90GHz		225GHz	
Elv (deg)	Winter	Summer	Winter	Summer
80	8.54	11.17	16.42	52.29
60	8.71	11.73	17.85	61.83
45	9.09	12.88	20.71	82.81
20	11.87	20.75	41.9	345.41

And at the OSF (median conditions):

Flicker Noise (Jy)	90GHz	225GHz
Elv(deg)		
80	7.79	19.66
60	7.86	20.64
45	8.04	22.56
20	9.56	35.98

These tables show that:

-Irrespective of the site, we are currently dominated by the 1/f noise of the receiving system for continuum observations!!! The only way around it (without nutators) would be to reduce the time samples to ~10msec or less.

-Even if the 1/f levels are reduced, from the current specs, by an order of magnitude, we will still have to use short integrations per sample for the thermal noise to dominate over the flicker noise to ~100msec or less.

-For spectral observations, we should be able to overcome the 1/f limitation and the atmospheric fluctuation effects just by fitting a baseline.

General Summary:

1) The OSF will on average be comparable or better than the best weather expected at the ATF
2) The current ALMA specifications for the Trx and backend BW make the system quite sensitive (@ 90GHz and 225GHz) for continuum observations at either site
3) With the current ALMA specifications, the noise levels for switched continuum observations are ordered in decreasing importance as: flicker noise → Atmospheric Fluctuations → Thermal Noise, for any switched observations with ON times above ~0.5sec. The only way around this situation is to reduce significantly (~10msec) the integration times of the samples. This is obviously unrealistic for switched observations without nutators. We are therefore left with the situation that most of the "measurements" in continuum we will be making will actually be 1/f-noise dominated unless RX systems with Gain stabilities ~1e-4 are provided (and/or we get the nutators in time). Spectral-line modes woill not be affected by this limitation.